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t; DEVELOPMENT OF WEAVE BEAD TECHNIQUES
FOR MULTIPASS VERTICAL MIG WELDING
OF ALUMINUM ALLOYS Final Report

National Aeronautics and Space Administration
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DEVELOPMENT OF WEAVE BEAD TECHNIQUES FOR MULTIPASS VERTICAL MIG WELDING OF ALUMINUM ALLOYS

Final Report,

(NASA CR-55902;

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DEVELOPMENT OF WEAVE BEAD TECHNIQUES FOR MULTIPASS VERTICAL MIG WELDING OF ALUMINUM ALLOYS

ABSTRACT

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The purpose of this program was to define the parameters of a machine controlled wide-weave technique for performing vertical-up welds in thick aluminum plates, and to develop a machine to perform the automatic weld so defined. To arrive at a welding technique of sufficient latitude that reproducible high quality would be assured, programmed oscillation parameters were sought. The first step was to study the techniques of manual welders in performing similar welds. These studies defined oscillation parameters which gave satisfactory welds.

A machine to provide these motions was then developed and evaluated as an automatic welding device. Satisfactory welds were made with this machine when simulating the simpler techniques employed successfully by skilled manual welders.

In addition, other techniques not generally available to manual welders were given brief evaluations. Although no marked benefit was derived by using more complex programs, some improvement was indicated over the best obtainable within the limitations of manual techniques. Further study is required to develop the potential of this welding method.

AUTHOR

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DEVELOPMENT OF WEAVE BEAD TECHNIQUES FOR MULTIPASS VERTICAL MIG WELDING OF ALUMINUM ALLOYS

I. INTRODUCTION

Ever larger missiles and rockets are requiring, as they come along to replace previous generations, the joining of thicker plates and longer seams. These geometry changes do not, of course, ease the usual requirement for very high quality. The accomplishment of these seams is made more difficult by the fact that the larger structures are too cumbersome to be positioned for most convenient welding; they must be fabricated in the launching attitude. These factors explain the need for the development of fully or largely automatic welding techniques for performing high-quality seams in thick aluminum plate in the vertical plane.

Two approaches to this problem are the MIG and the TIG welding processes. Both of these are quite adaptable to aluminum welding, and have been successfully applied in vertical plane welding. However, past practice has used either manual welding, or stringer-bead automatic, or semiautomatic techniques. The improvements that this program sought to develop over manual welding were (1) increased reproducibility and reliability, (2) elimination of operator fatigue considerations, and (3) the elimination of arc stop and restart areas. On the other hand, advantages sought over automatic stringer-bead techniques were (1) the deposition of more metal per pass; (2) reduction in number of passes and therefore a reduction in the time necessary for the machine to retrace to the starting position; (3) reduction of interpass cleaning (fewer passes); and (4) reduction of travel speed, and attendant reduction in precision requirements for tracking and groove design, for a given amount of metal deposition.

This program has been restricted to the development of filler pass (i.e., excluding the initial, or root pass) techniques for automatic vertical MIG welding of 3/4 and 1 in. 5456 aluminum plates with 5356 aluminum wire electrode. The initial, or root pass problem is the subject of other programs and concerns different techniques.

In conducting this program, the philosophy was adopted of letting a welding machine learn from one or more expert welders. It was known that expert welders had developed wide-weave vertical welding techniques. The plan, therefore, was to study manual welder techniques and to develop equipment that would duplicate these techniques. The program resolved itself into three parts: (1) recording the manual welder wide-weave vertical techniques, (2) developing equipment to duplicate the techniques, and (3) reducing these techniques to the minimum requirements. The major shortcoming of automatic simulation of manual techniques, it is recognized, is the inability to feed correction information back to the control device--the human being is still a very efficient feedback control. However, part of the complex feedback information that is essential in manual welding may not be necessary for automatic welding, since an automatic machine may provide improvements on form and consistency of a given technique. A manual welder, in a sense, consistently corrects for his own errors. Thus, the welding techniques developed for the automatic welding device might be simpler than those employed manually, and might have wider latitude of allowable deviation. Another factor to offset the loss of feedback control is that the machine can perform mechanical operations which a manual welder cannot, especially over a long time period. The machine can be faster, stronger, and more reliable.

II. DEFINITION OF DESIRABLE WELDING TECHNIQUE

A. General Considerations

Successful welding techniques--whether manual or automatic--must meet certain fundamental requirements. A discussion of these is in order, for it will point out the difficulties which had to be surmounted in mastering both manual weld techniques and their automatic counterparts. In joining two pieces by a fusion welding process, a certain amount of metal must be melted to form a puddle. This puddle must be manipulated to come into contact with hot solid metal in such a way that it will fuse to the parts to be joined and provide a continuous bridge of desired geometry between these parts after solidification. This problem has two aspects: metal must be supplied to the proper places, and heat must be supplied to the proper places. Both metal and heat addition must be balanced to provide a satisfactory weld bead. In arc welding, we are faced with the limitation that the arc supplies both heat and filler metal, and therefore the two variables are not independent. Perhaps this is why oxyacetylene welding is easier for the beginner to learn than arc welding; in oxyacetylene welding, heat and filler metal can, to some extent, be added independently. The arc welder can achieve some degree of independence between metal and heat addition by using the force of the arc to blow the filler metal to the desired spot.

One of the difficulties with welding in a deep groove is obtaining proper fusion at the sidewalls of the groove. One flaw, illustrating a type of unsatisfactory adjustment of metal and heat at the sidewall, is "undercut." The arc heat melts away the sidewall metal, and arc force then blows the metal away.

Another frequently encountered sidewall flaw is a "cold lap," or "lack of fusion." This deficiency is caused by the opposite imbalance--excess filler metal and insufficient heat. A less extreme version of this same flaw is a convex weld bead. In this case, the sidewall is so cold that the wetting angle is quite large, usually greater than 90°. This leaves a re-entrant corner between bead and sidewall which is difficult for subsequent beads to fuse. Poor fusion between the liquid puddle and the solid metal can also be caused by excessive weld travel speeds; the base metal is not heated sufficiently to fuse to the liquid metal. (Or, the wetting angle between liquid and cool solid metal is too great.)

Poor fusion can also be caused, particularly with aluminum, by insufficient removal of the oxide scale on the solid. In the MIG process oxide is removed by cathodic arc action; its nonremoval can be caused by failure of the arc cathode to sweep that particular area.

Thus the challenge of developing a satisfactory weld technique can be defined primarily as that of generating a proper balance of filler metal and arc heat at every point in the weld bead area. An excess of either will cause a flaw similar to one of those described above.

B. Observations of Manual Welding Techniques

All of the welding experiments conducted on this program, both manual and automatic, were performed with one of the three joints whose cross section is shown in Figure 1. These joints were chosen to provide an example of a very narrow groove (20°), a groove which is wider than normally deemed necessary but having a width typical of those found for thicker plate welds (90°), and an intermediate groove angle (60°). The base plates were 3/4 to 1 in. thick 5456 aluminum alloy. Filler wires were 3/64 in. 5356 alloy. Argon shielding gas was used with a standard commercial pull-type wire feed gun (Air Reduction Model AH-35A).

The intent of this program was not, of course, to mathematically derive an ideal weld technique according to the principles outlined; the heat flow and arc force variables involved are much too complex for such analysis. Instead, the more modest objective was to accurately describe a technique that was observed to be satisfactory when employed by a manual operator, and to develop a machine that would provide these same techniques automatically, hopefully with sufficient latitude that a feedback control device would not be required.

The first attempt to record the minute details of an operator's technique was to instrument the movement which the torch makes when manually controlled by a skilled operator. This requires a minimum of three linear measurements and three rotational measurements. In the apparatus pictured in Figure 2, additional linear measurements were substituted for the rotational measurement requirements. In all, 14 strings, arranged as 7 opposing pairs, were attached to the torch from spring-loaded reels. As each string extended from or returned to the reel, a potentiometer was twisted and an appropriate electrical signal recorded the movement. Analysis of all 14 records would give a complete description of the movements made. However, it is readily apparent that this analysis can be quite complicated and that considerable work is required to reduce it to a useful form. Also, it was found that the string tension necessary (to insure that the potentiometers would follow accurately) and the friction in the potentiometers resulted in a system which encumbered the welder to an undesirable extent. Satisfactory welding could be performed with this device, but it was difficult and the techniques observed could not be assumed typical of a free-movement manual weld.

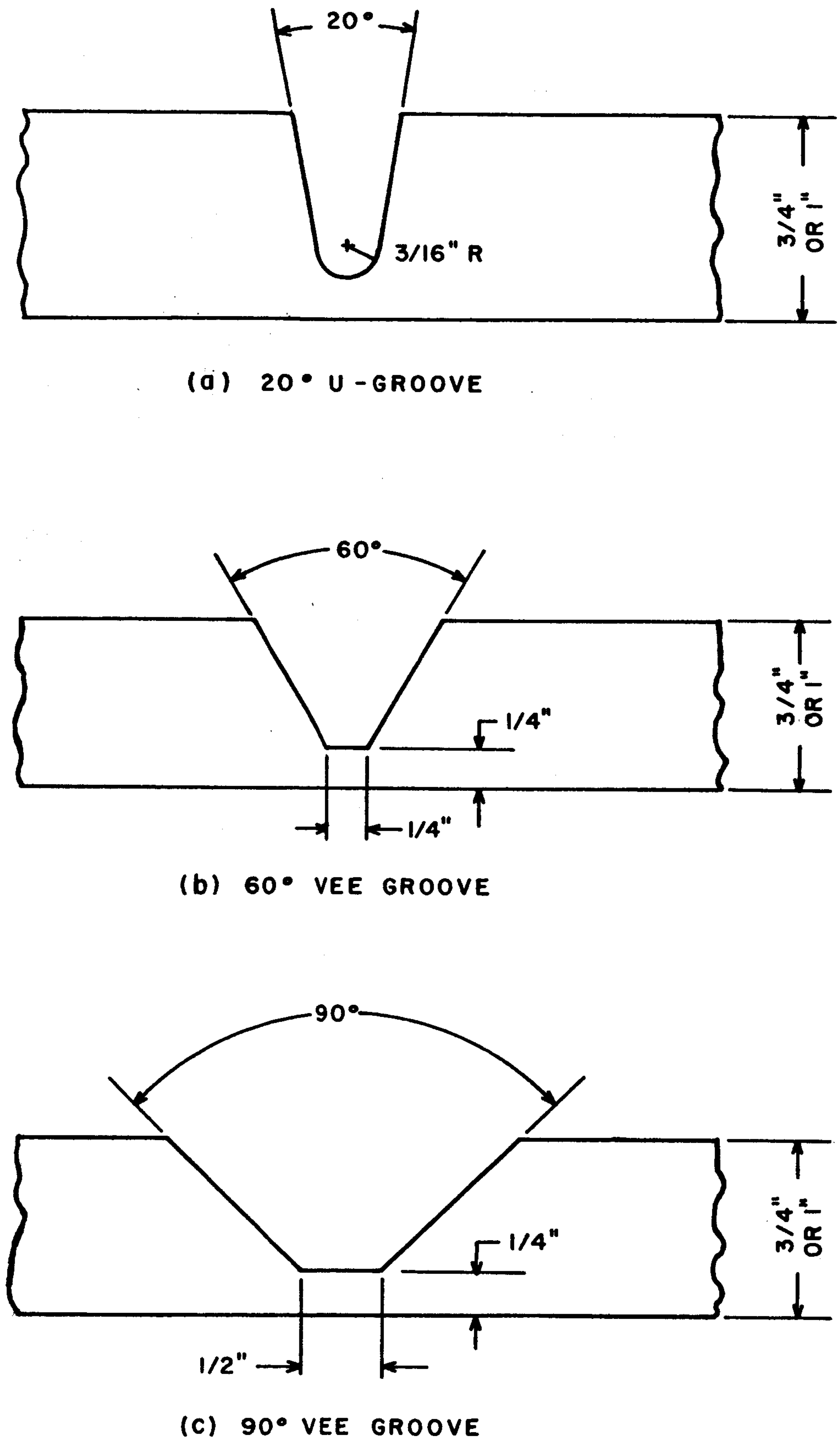

FIG. 1 - JOINT CROSS SECTIONS.

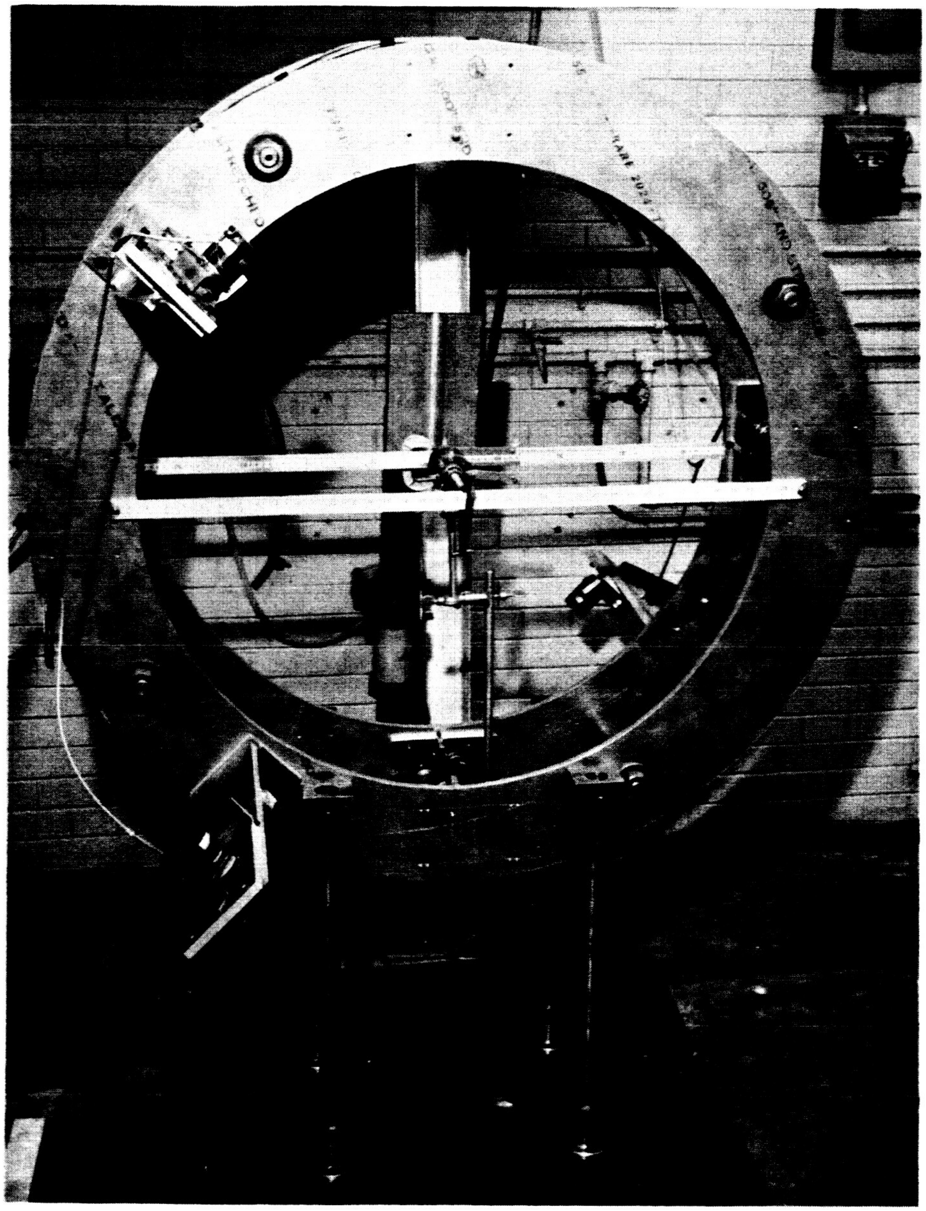

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FIG. 2 - FRAMEWORK AND LINEAR MOTION SENSORS FOR ACCURATELY OBSERVING A MANUAL WELD. The torch was held at the center of the circle to weld the plate shown in the background.

The typical displacement signal traces (Figure 3) illustrate that the apparatus of Figure 2 has excessive friction. The displacement traces tend to be stepwise, indicating that the welder in performing his motions overcomes a given amount of friction, then hesitates at zero motion as long as he can, and then forcibly moves the torch another increment.

A second, more modest device was successful in providing useful records of a manual welding technique. With this device it was not attempted to give the welder complete freedom of movement; movements in some modes were restricted. This simplified the instrumentation problem, and at the same time left some freedom for control of the torch; a welder could produce a satisfactory bead within these limitations. This device is pictured in Figure 4 and is simply a system for holding the torch which allows sliding motion in one direction (transverse to the weld direction), and rotation about horizontal and vertical plane axes which are normal to the torch axis. Also with this device, any one or two of the three possible modes could be locked in position, thus allowing freedom in only two or one motions. Interesting and useful information was obtained with this experiment when only transverse weaves with and without longitudinal weaves were allowed. These weave motions were obtained through oscillatory rotations about the θ or ϕ axes. (The various motions and rotations are defined for convenience in Figure 5.) Oscillograph traces obtained of experiments performed in this manner, are shown in Figures 6, 7, 8, and 9. It can be seen that the welder did not use freedom of ϕ (longitudinal weave) to any great extent. In one case ϕ is constant, and in the other three the adjustments are minor. The welder seems to automatically seek a forehand angle (ϕ) of 10° to 15°. This observation was verified by subsequent movie observations of welds made with complete freedom. In all the above experiments, travel speed (uniform linear motion parallel to the Z' axis) was maintained constant throughout any one weld. Current and voltage vary somewhat; higher current is used on the first and cover passes.

For a manual operation, the oscillation patterns and repetitions are remarkably consistent. The trace of Figure 6 shows six oscillation cycles, and illustrates that both frequency and amplitude are accurately maintained. As the weld becomes wider, going from first to cover pass

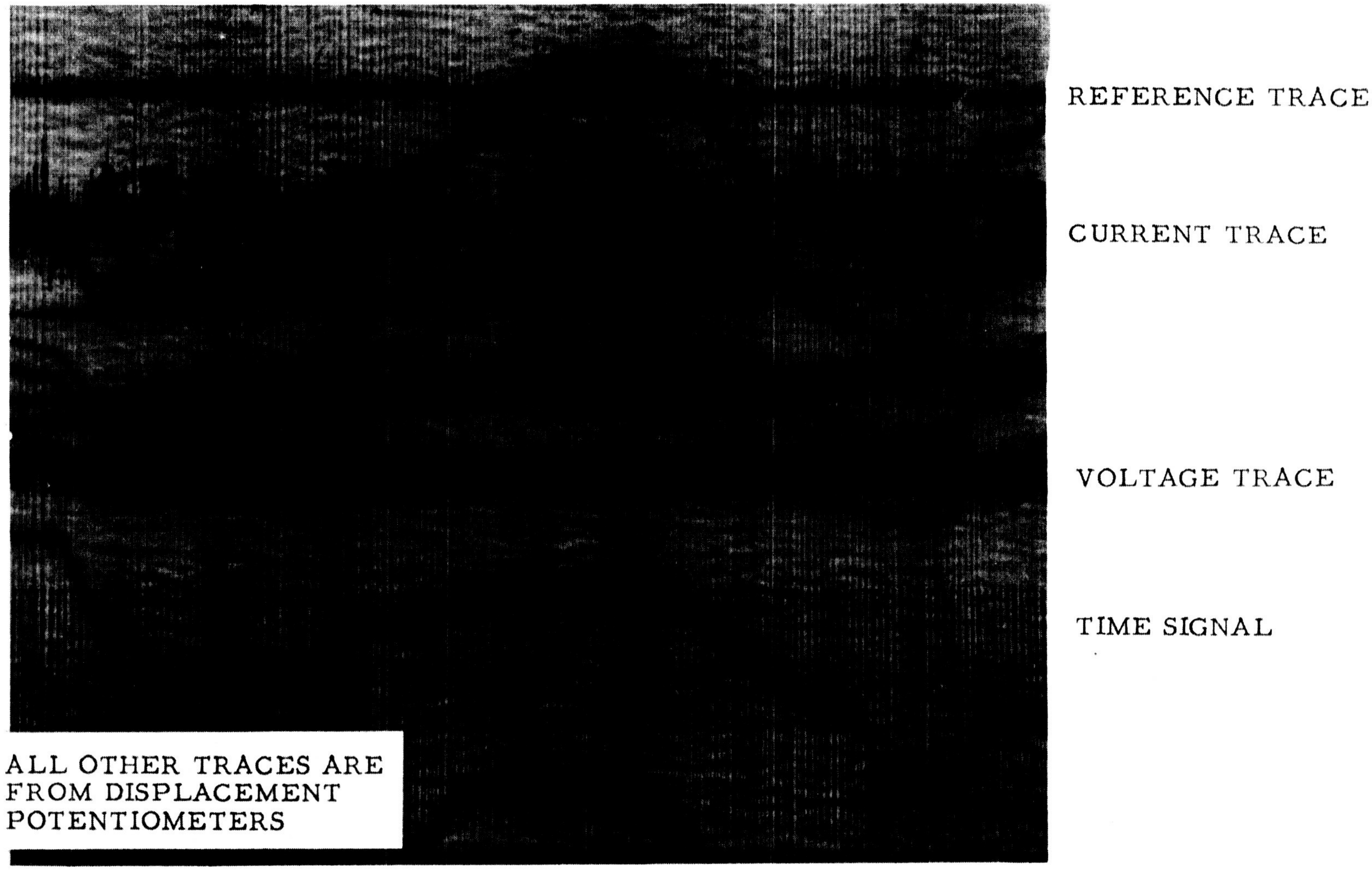

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FIG. 3 - TYPICAL DISPLACEMENT TRACES OBTAINED DURING A FREE MANUAL WELD WITH THE APPARATUS OF FIG. 2. The 11 sharp, distinct lines are displacement traces; current, voltage, and timing traces are also shown.

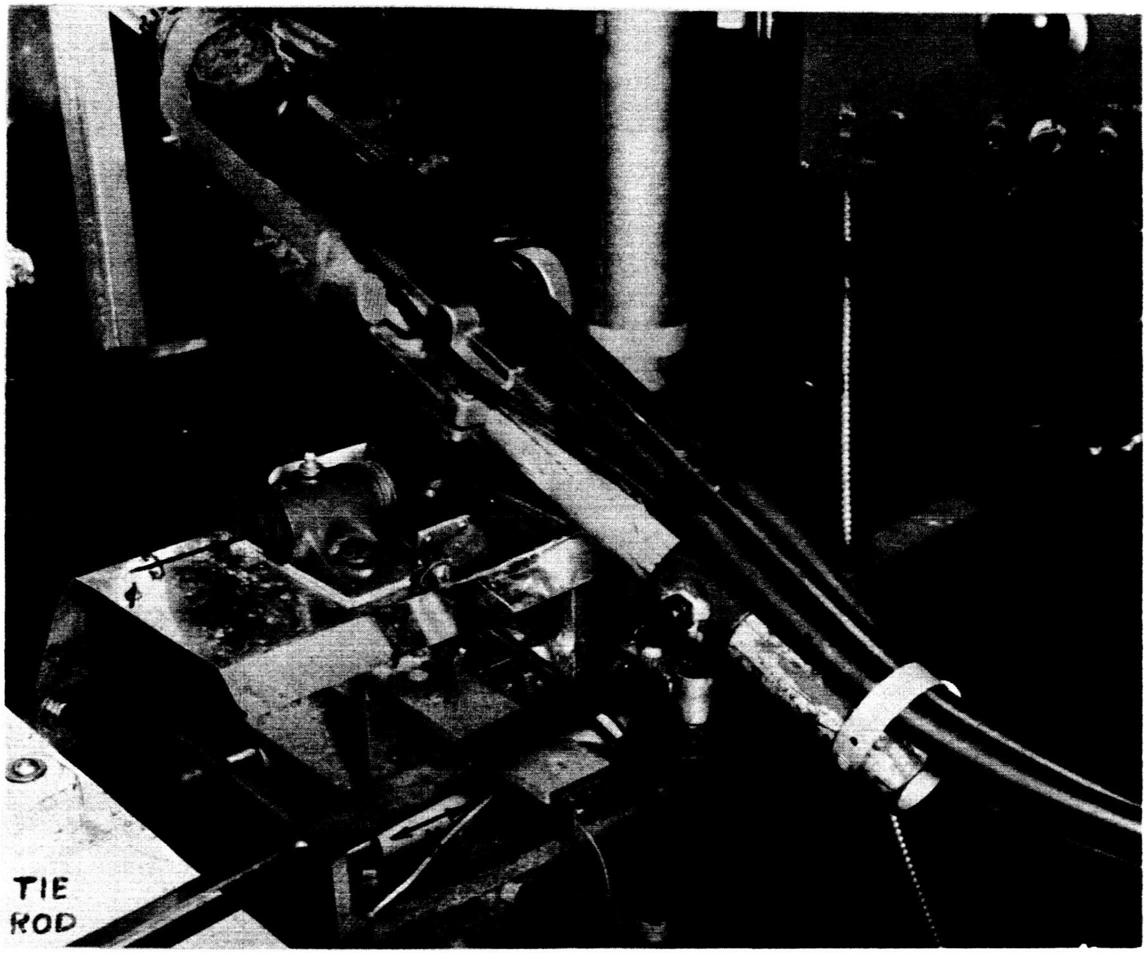

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FIG. 4 - WELDING TORCH SUPPORT. This apparatus allows freedom of θ, ϕ, and/ or X motions; all of these motions are tied to a potentiometer for instrumentation. For manual operation the tie rod is disconnected.

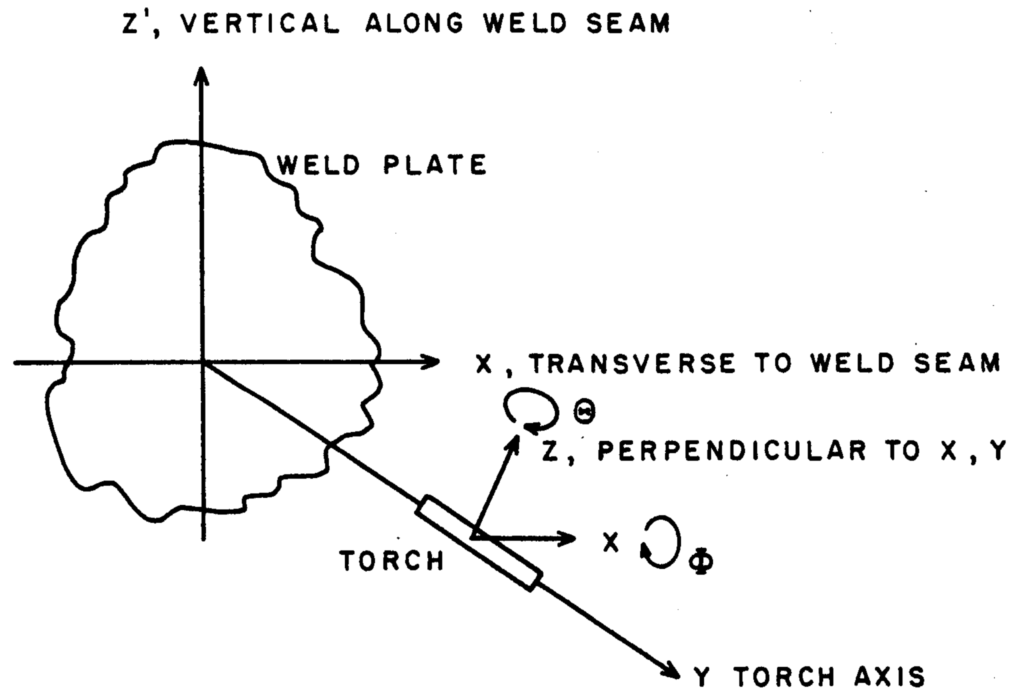
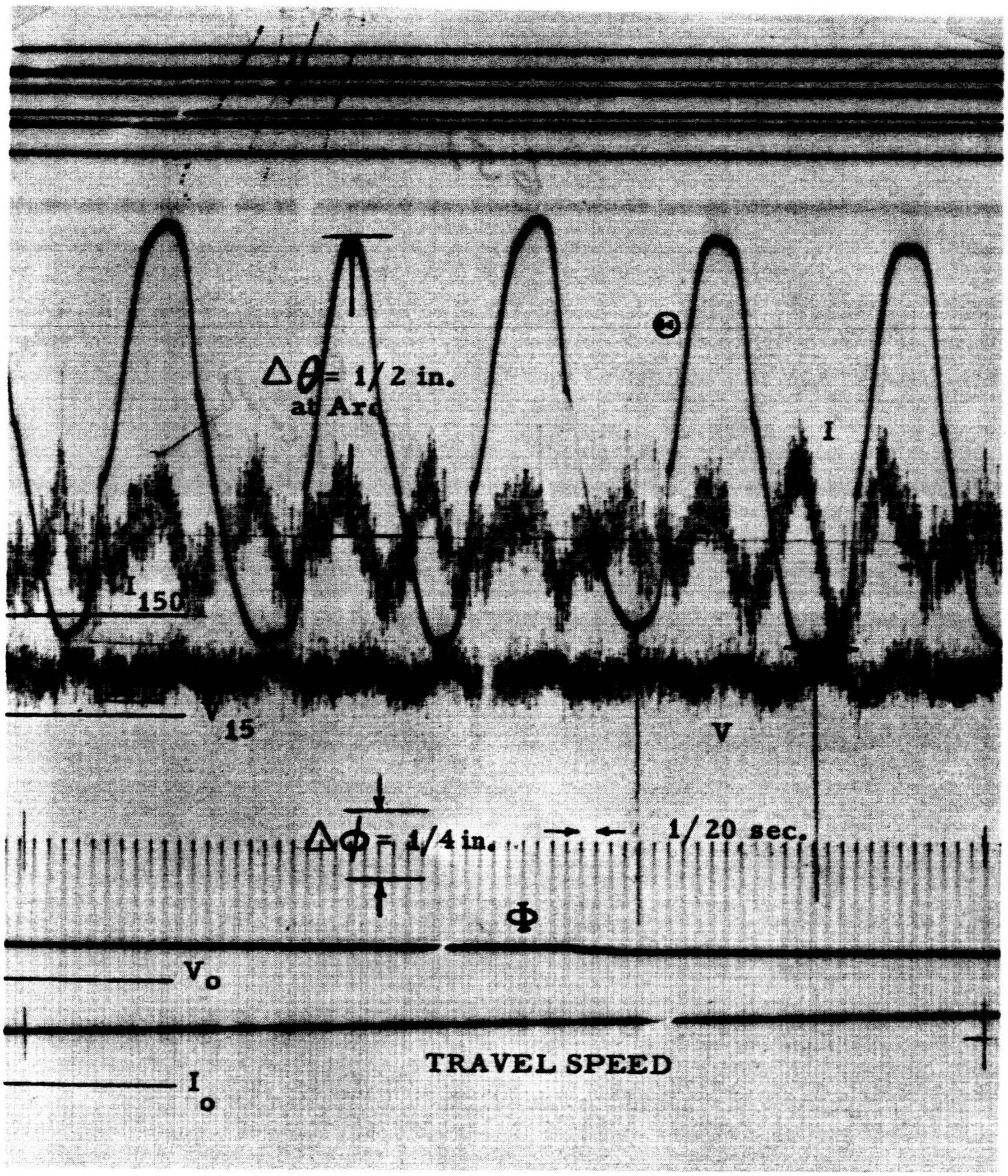


FIG. 5 - DEFINITION OF ROTATION AND TRANSLATION SYMBOLS.
Z is only parallel to Z' when $\phi = 0°$ from the horizontal plane.



Trace No. 27651

FIG. 6 - PARAMETER TRACES FOR MANUAL FIRST-PASS WELD.
Transverse oscillation (θ) and forehand angle (ϕ) were free; other parameters were "constant."

I = 170 amps
V = 17 volts

θ = 0.71
f_θ = 100 cpm

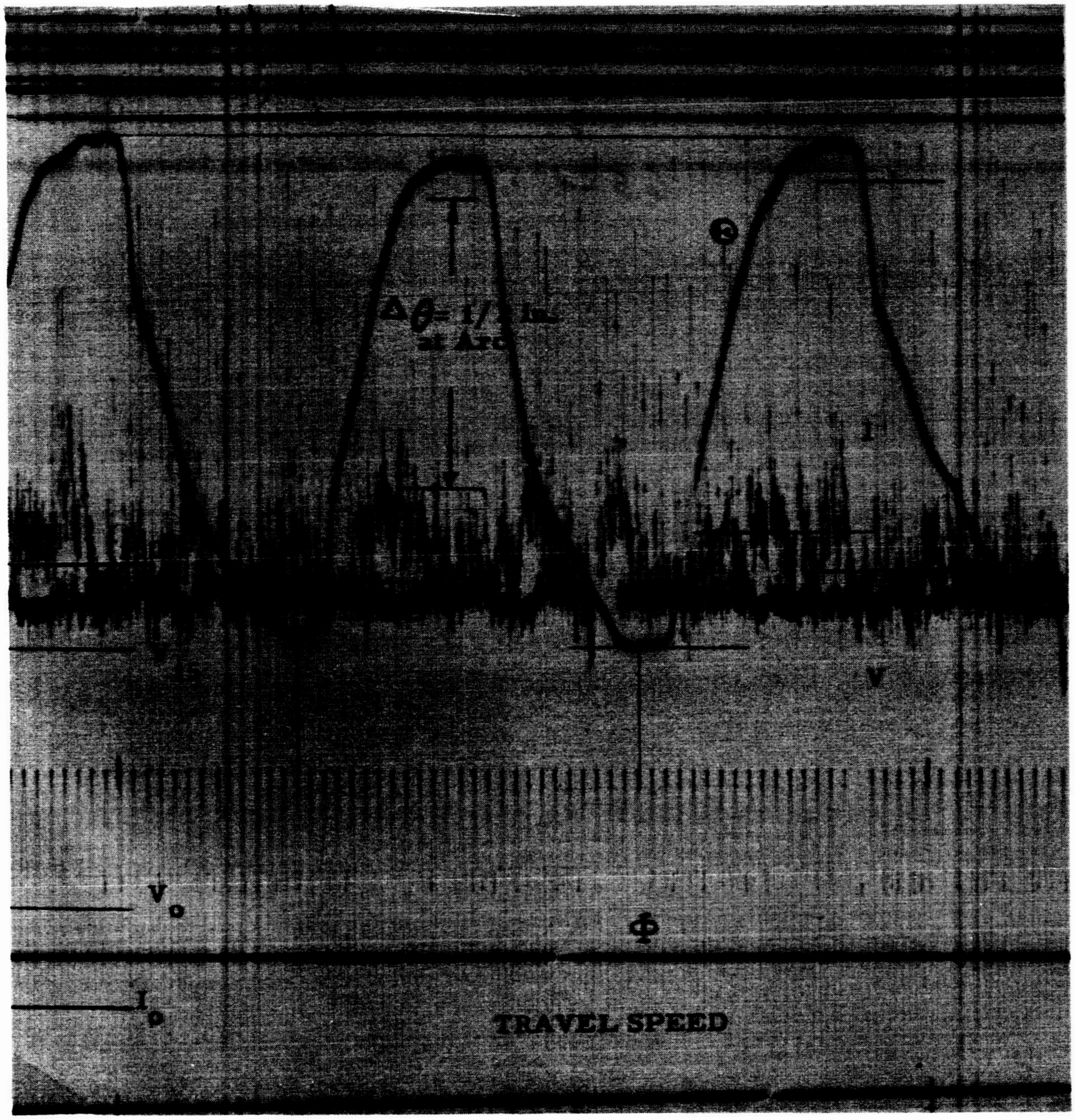


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FIG. 7 - PARAMETER TRACES OF SECOND-PASS MANUAL WELD, WITH SAME DEGREE OF FREEDOM AS FIG. 6.

$I = 155$ amp	$\theta = 0.88$ in.
$V = 18$ volts	$f_{\theta} = 48$ cpm

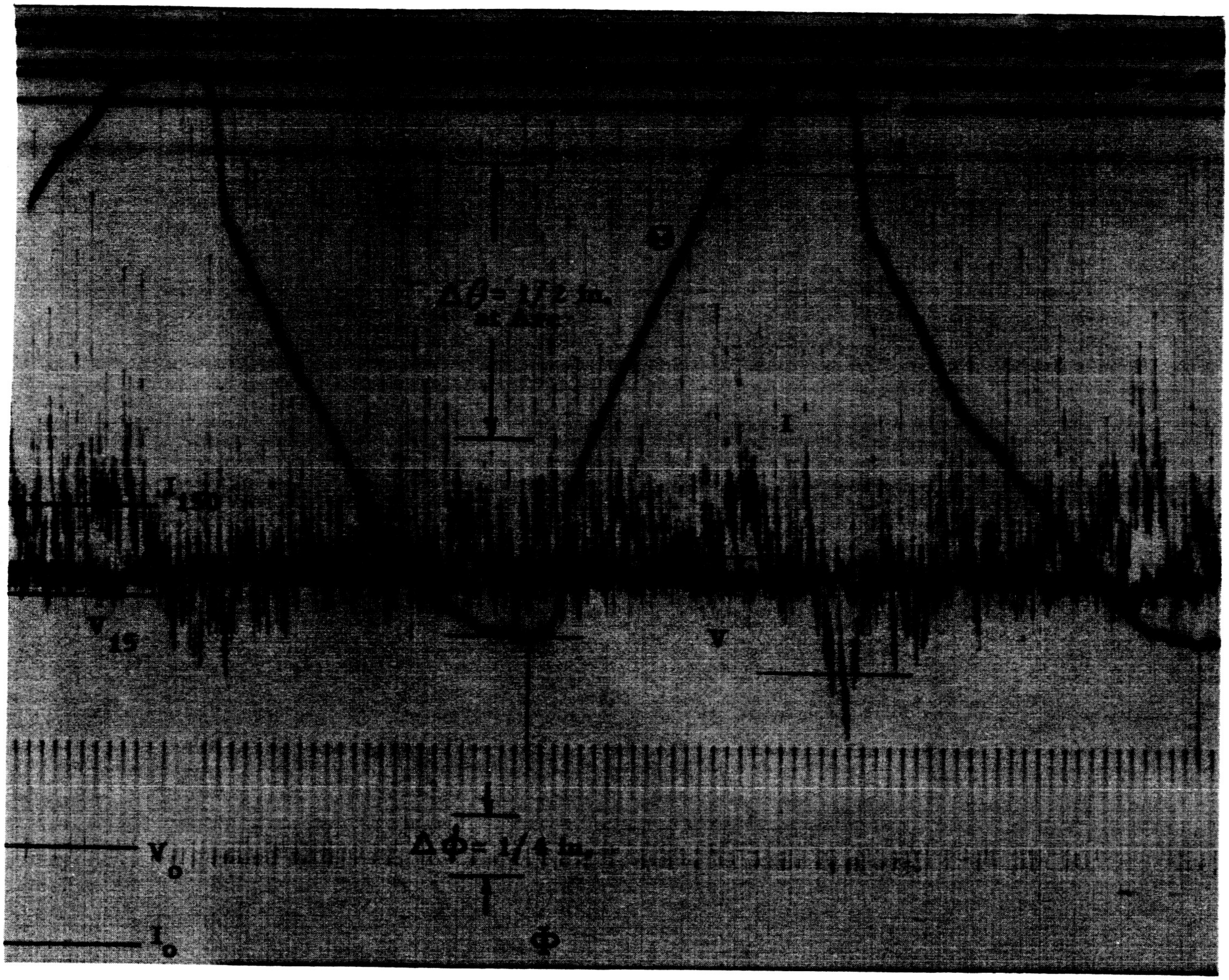

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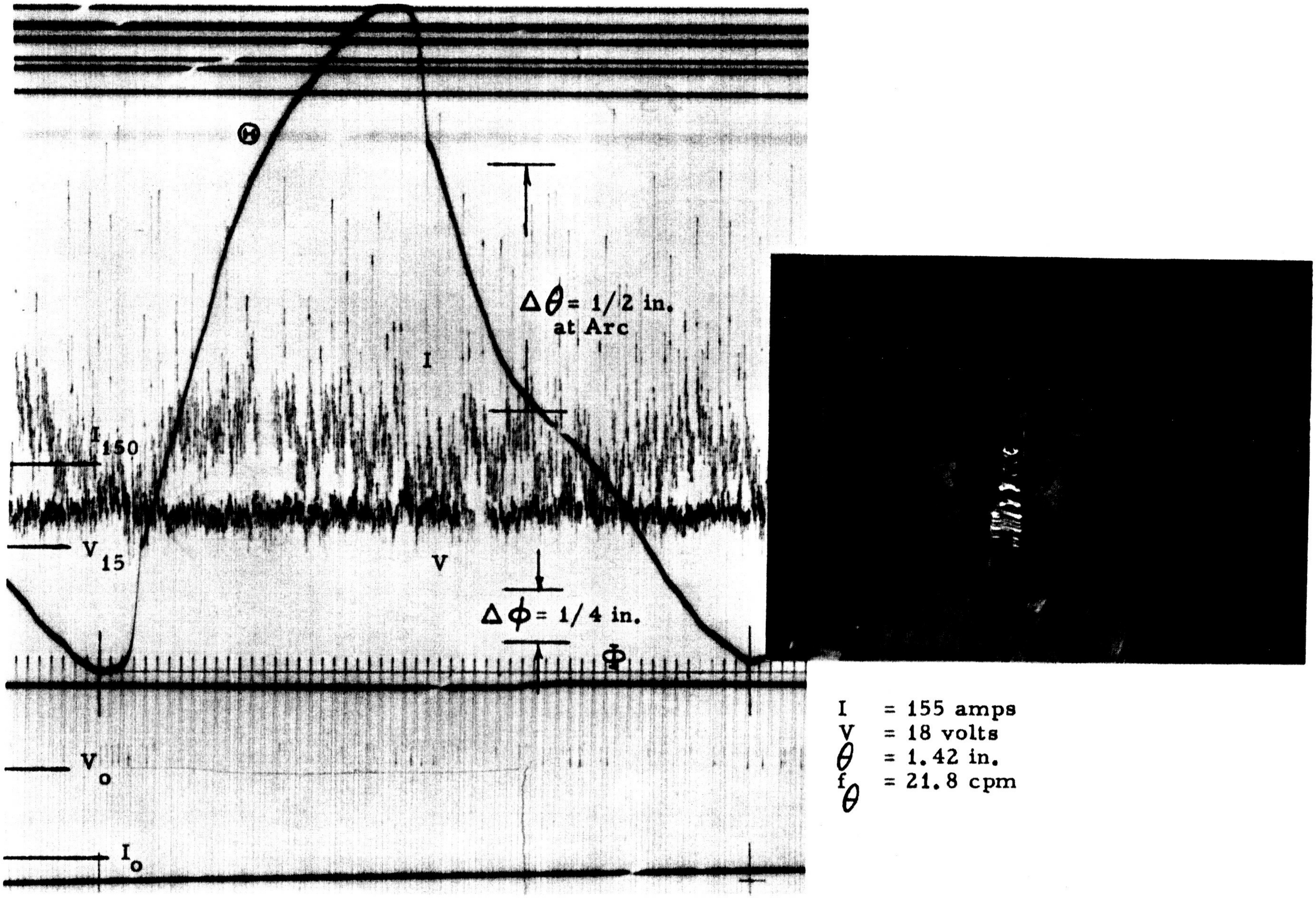
FIG. 8 - PARAMETER TRACES OF THIRD-PASS MANUAL WELD, WITH SAME DEGREE OF FREEDOM AS FIG. 6.

I = 130 amps $\quad\theta$ = 1.05 in.

V = 17 volts $\quad f_\theta$ = 24 cpm



I = 155 amps
V = 18 volts
θ = 1.42 in.
f_θ = 21.8 cpm

Trace No. 27657

FIG. 9 - PARAMETER TRACES OF FOURTH-PASS MANUAL WELD AND PHOTOGRAPH OF ALL FOUR PASSES.

(Figures 7, 8, and 9), the half-cycles are less symmetrical and the frequency decreases by several multiples. Since time is moving from left to right in the traces, the asymmetry means that the arc approaches the sidewall at considerably less velocity than it leaves. The pattern is slow approach, a momentary dwell, and rapid removal. Evidently, the welder senses when the heat is just short of that point at which the metal is about to escape from the area, and prevents this escape by rapidly moving the arc away.

Some qualitative conclusions can be drawn from the data so obtained:

(1) The width of the weld bead is critical; too wide a weave width with respect to the groove width accentuates undercut.

(2) A relationship exists between frequency of oscillation and travel speed; at a travel speed of 6 ipm an oscillation of 60 to 100 cpm is appropriate.

(3) If the oscillation frequency is too low, the weld takes on a "ropy" appearance, as shown in Figure 10, whereas an excessive oscillation frequency makes control of the weld difficult. Part of the latter is due to welder fatigue, although whipping of the electrode wire can also become a problem. The limitations in the direction of high oscillation frequency are more restrictive for manual welding than for automatic welding, although higher frequencies will introduce some difficulties in the automatic design as well.

(4) The forehand angle (ϕ) can vary between approximately 8° and 15° from the plane of the plate being welded. Too small an angle accentuates undercut, possibly because of the enhanced effect of arc force; too great an angle allows the arc to strike from the trailing (lower) side of the electrode wire onto the preceding traverse bead. The latter melts the retaining lip of the puddle cavity and allows the weld metal to roll out of the joint, causing cold laps near the surface and porosity in the root of the weld.

(5) It was found that a relatively low arc voltage, and an over-all travel speed of approximately 3 to 7 ipm are desirable. The upper limitation of travel speed is, for the weave patterns studied, a function of the problem of weld wire control at higher oscillation frequencies. Larger welding wires may alleviate this problem.

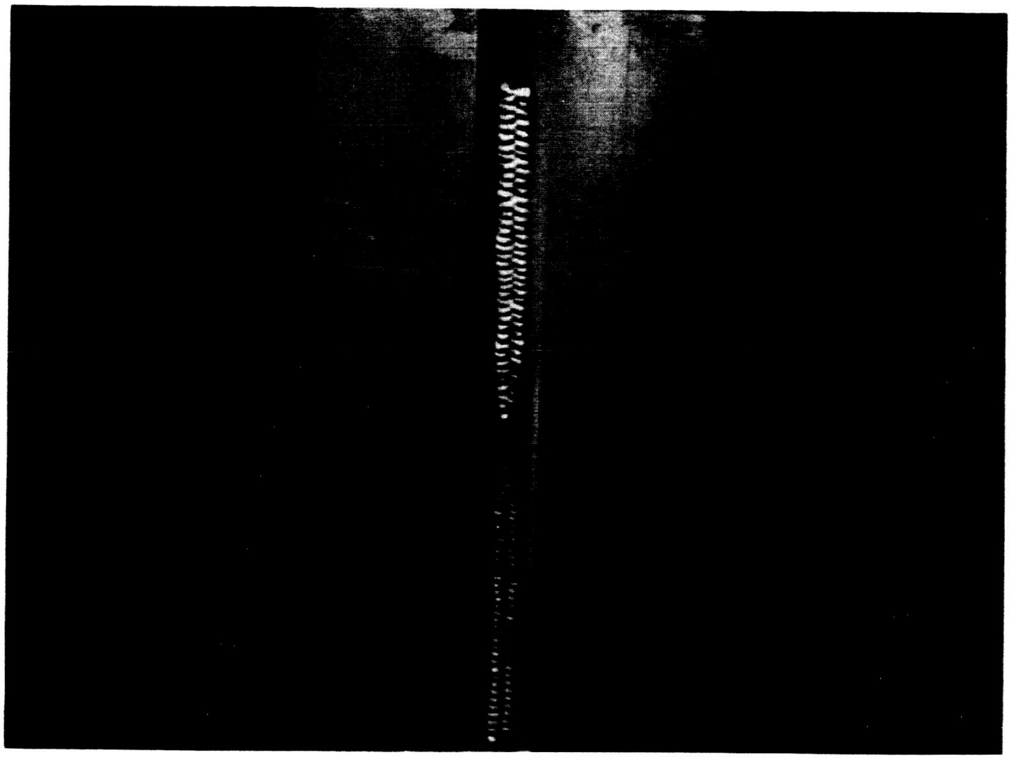


FIG. 10 - TYPICAL "ROPY" WELD,
DEPOSITED MANUALLY.

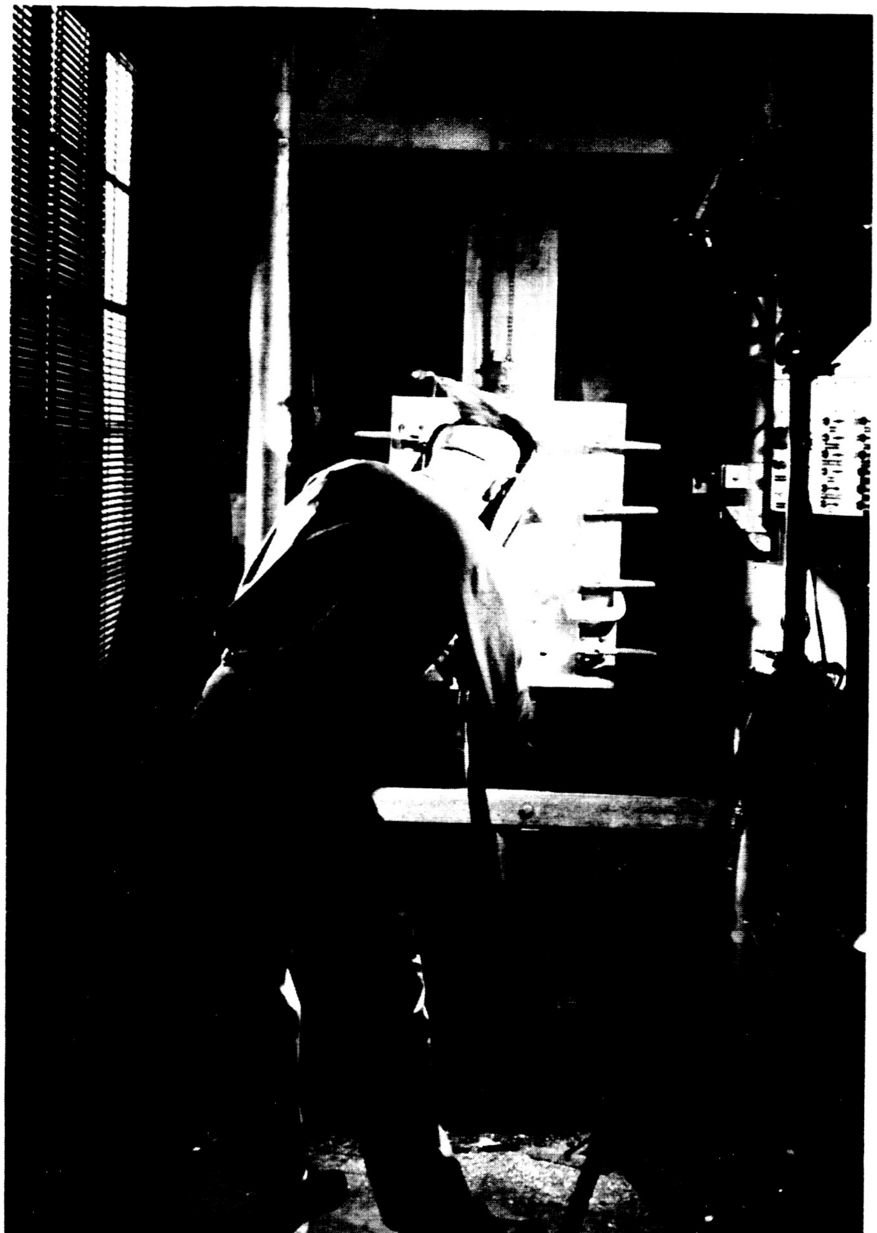
(6) As pass sequence increases, the weld bead becomes wider and therefore the oscillation angle θ becomes greater. This requires that the oscillation frequency--and, therefore, the travel speed--be decreased, if the "ropy" appearance is to be avoided.

(7) There appears to be a slight dwell at the end of each oscillation; this dwell increases in absolute time per oscillation, but becomes a decreasing proportion of the total time, as the pass width increases. The cover pass has very little deliberate dwell.

(8) It was also noted that increasing the weave amplitudes and frequencies introduces difficulties in maintaining adequate inert gas shielding. Higher gas flow rates and larger nozzle diameters should be used with the weave technique as compared to stringer-bead techniques. This problem will become more important as plate thicknesses increase if it is necessary to introduce all the shielding gas from the near surface of the plate.

The final experiments to analyze a manual welder's movement were performed with the aid of motion picture cameras. These experiments gave absolute freedom of movement. Two skilled welders, employed by a large local fabricator, cooperated with these experiments. These men were experienced in the particular joints of interest in this program--vertical MIG welding of heavy aluminum plate. Movies of each welder were taken simultaneously by three cameras, located as shown in Figure 11: one above the welder, one to the side of the welder, and one looking over the welder's shoulder. Typical observations are shown in Figure 12. All welds were made in the vertical position using wide-weave technique in the 20°, 60°, or 90° grooves shown in Figure 1. As before, the welds were made in 3/4 and 1 in. thick plate of 5456 aluminum. These results were quite interesting, partly because of the increased experience of the welders observed and also because of the increased freedom allowed the welders with this experiment. When asked to fill the joints in a single (filler) pass, the two welders used techniques which were completely different from one another, and it was possible to definitely rate the welders according to quality of weld obtained. One used a side-to-side weave pattern as illustrated in Figure 13a. (This pattern may have been slightly distorted to an oval shape.) The other used either the triangular or the chevron patterns illustrated in Figures 13b and 13c. The latter patterns were more effective

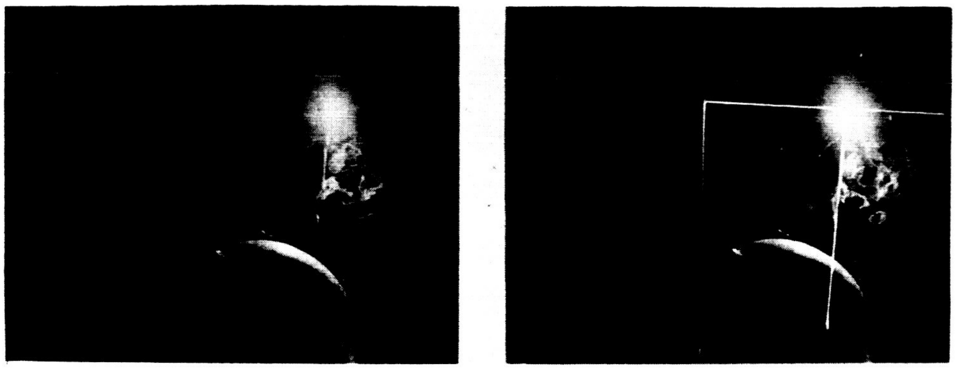
Camera A
looks directly
down.



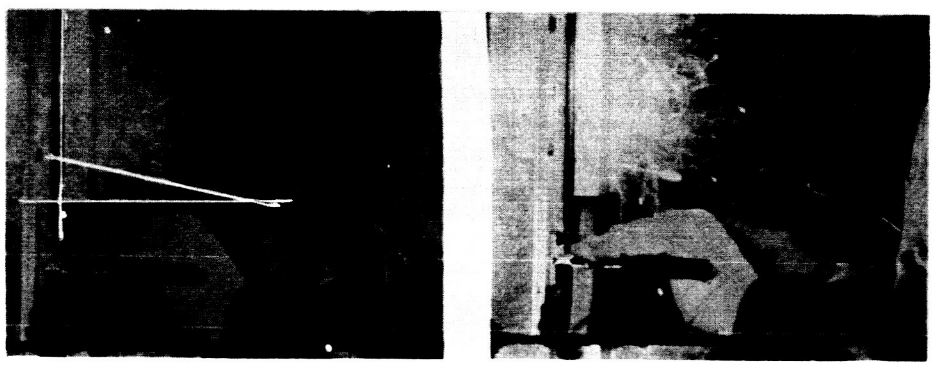
Camera B
looks over
welder's
shoulder.

Camera C
photographs
side view of
welder.

FIG. 11 - LOCATION OF CAMERAS FOR MOVIES OF MANUAL WELDING TECHNIQUES.



Camera A - Looking down



Camera C - Looking from side

FIG. 12 - SINGLE FRAME PHOTOGRAPHS TAKEN FROM MOVIE OBSERVATIONS OF MANUAL WELDING.

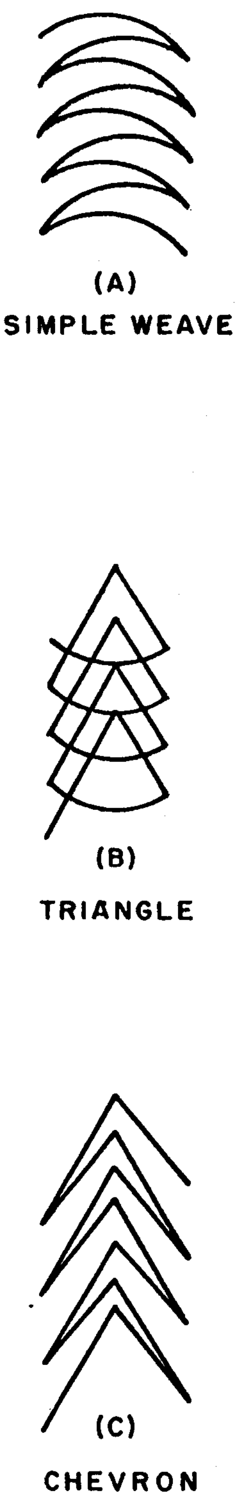
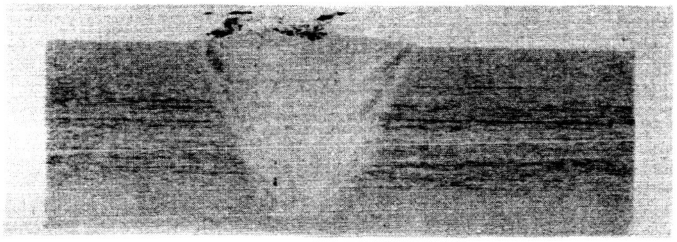


FIG. 13 - WEAVE PATTERNS USED BY MANUAL WELDERS DURING VERTICAL WELDING.

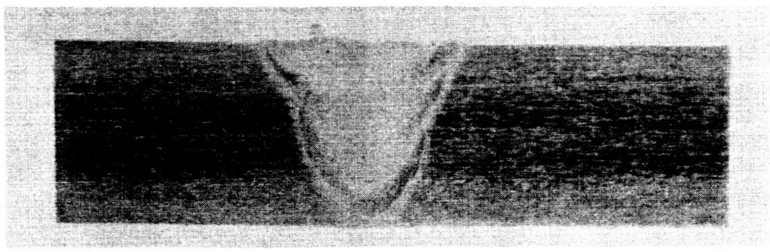
in filling in a minimum number of passes, giving good quality, sufficient fusion, and good appearance. Joints with 20° U-grooves in both 3/4 and 1 in. plate could be filled with one pass, although this was considered to be a challenge by the welders; 60° grooves were easier to handle. Figure 14 shows typical cross sections of welds made by the chevron and triangle patterns in 20° U-grooves. All were single (filler) pass welds in 3/4 in. plate with similar welding heat inputs. It is interesting to note that the 2° to 14° variation in forehand angle has apparently little effect. Weave cycle frequency is less uniform than reported above with the semicontrolled weave pattern, Figures 6-9, and ranges from 20 to 48 cpm. The time of dwell at the sidewall seems shorter with the triangle pattern, than with the chevron. The same welder, when instructed to use a weave pattern with similar groove and welding heat input, kept approximately the same weave cycle frequency (21-29 cpm), but had to go to a two-pass technique, giving the weld shown in Figure 15a. With a 90° included angle, he went to a three-pass technique, and here the influence of the widening bead shows on the weave cycle frequency. The first pass, with a 1/2 in. root width, has a weave frequency comparable to above (24-26 cpm), but the second and third passes have decreasing frequencies (16-17 and 10 cpm, respectively) which reflect the increased pass width. Travel speed also slows as the frequency decreases with wider passes. These data are summarized in Table I.

The second welder (No. 3 in Table I), with the one-dimensional weave technique for 20° U-groove welds in 1 in. aluminum plate (Figure 13a), shows an interesting variation in weave frequency for the three-pass weld shown in Figure 16b. The first pass is deposited with a higher, although less consistent (29-41 cpm) frequency than welder No. 2 used; the second pass was considerably slower (19 cpm); and the cover pass was then deposited with a somewhat greater frequency (26 cpm). This pattern was repeated by the same welder with a 60° V-groove as shown in Figure 16c. This was a four-pass weld, and the cover pass was again higher frequency than the pass just prior to the cover pass (29, 29, 22, and 29 cpm, respectively). This suggests that the reduced heat sink in the cover pass would require a higher frequency, for a given bead width and travel speed, than comparable passes down in the groove. Also, this



(a) Chevron pattern, 22-29 cpm, 14° forehand angle, 17% dwell at sidewalls

(b) Triangle pattern, 20-48 cpm, 8° forehand angle, 10% dwell at sidewalls



(c) Chevron pattern, 30 cpm, 2° forehand angle, 25% dwell at sidewalls

Neg. No. 24025

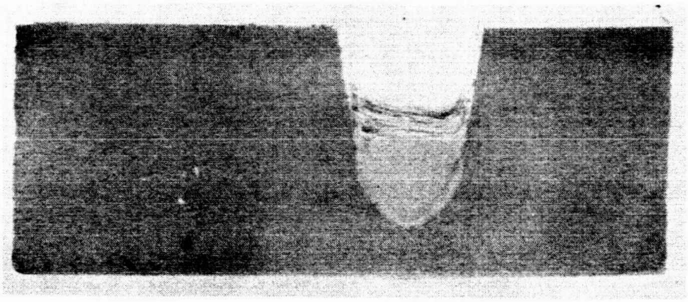
FIG. 14 - MANUAL WELDS MADE IN ONE PASS WITH TWO-DIMENSIONAL WEAVE PATTERNS. 20° U-groove, 3/4 in. plate, 170 amps, 26 volts.

(a) Two-Pass, 20° U-groove, See Table I

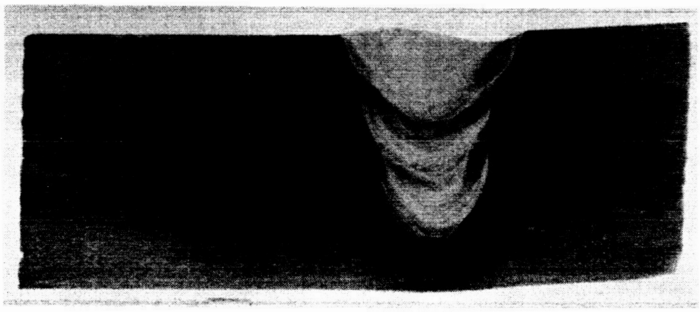
(b) Three-Pass, 90° V-groove, See Table I

Neg. No. 24207

FIG. 15 - MANUAL MULTIPASS WELDS MADE WITH SIMPLE WEAVE PATTERN.



(a) 1 pass, 20° U-Groove



(b) 3 passes, 20° U-Groove

(c) 4 passes, 60° V-Groove

FIG. 16 - MANUAL WELDS MADE WITH SIMPLE WEAVE PATTERN, See Table I.

TABLE I

SUMMATION OF OBSERVATIONS OF MANUAL WEAVE WELDING

Welder Ident.	Fig. No.	Pass No.	Groove Angle, deg	Current Amps	Volts	Travel Speed, ipm	Forehand Angle, deg	Oscillation Frequency, cpm	Oscillation Amplitude in.	Dwell Time Per Cent	Dwell Time Sec	Pattern
1	6	1	90	170	17	4.9	12	96	.71	33	.15	Weave
1	7	2	90	155	18	4.1	15	48	.88	45	.25	Weave
1	8	3	90	130	18	5.3	15	24	1.05	24	.20	Weave
1	9	4*	90	155	18	3.8	10	22	1.42	15	.15	Weave
2	14a	1*	20	170	24-26	3.5	14	22-29	-	-	-	Chevron
2	14b	1*	20	170	26-28	5.5	8	32	-	-	-	Triangle
2	14c	1*	20	170	26-28	3.3	2	29	-	-	-	Chevron
2	15a	1	20	170	26-28	~3.2	13	21-29	-	-	-	Weave
2	15a	2*	20	170	26-28	3.8	10	24-29	-	-	-	Weave
2	15b	1	90	170	22-24	~4	10	24-26	-	-	-	Weave
2	15b	2	90	170	22-24	~3	9	16-17	-	-	-	Weave
2	15b	3*	90	170	22-24	1.6	10	10	-	-	-	Weave
2	-	1	60	170	22	~3	8	19-26	-	-	-	Chevron
2	-	2*	60	170	22	2.8	4	15-20	-	-	-	Chevron
2	-	1	60	170	26-28	~7.8	8	48-58	-	-	-	Weave
3	16a	1	20	170	24	~1	13	32-36	-	-	-	Weave
3	16b	1	20	190	26	-	7	29-41	-	-	-	Weave
3	-	2	20	190	26	-	7	19	-	-	-	Weave
3	-	3*	20	190	26	4.2	8	26	-	-	-	Weave
3	16c	1	60	170-190	26-28	-	12	29	-	-	-	Weave
3	-	2	60	170-190	26-28	-	8	29	-	-	-	Weave
3	-	3	60	170-190	26-28	-	10	22	-	-	-	Weave
3	-	4*	60	170-190	26-28	6.4	11	29	-	-	-	Weave

* Cover pass

pass was lighter, and the base plate temperature was higher. The greater consistency in weave frequency with the 60° groove is probably indicative of less difficulty in controlling the puddle.

The 60° V-groove was preferred by both welders because they had difficulty preventing arc skipping in the 20° groove. (No intermediate groove angles were used.) This is caused by the tendency of the arc to jump from the root face to the sidewall, skipping the corner. This difficulty results primarily from the low angle of incidence between the sidewall and the electrode axis. A stiffer wire (1/16 in. instead of 3/64 in.) might have helped in the welding of the narrower groove, since it would enable more precise control.

Both welders appeared to move the gun tip side-to-side by rotating about a point approximately at the wrist, or slightly farther back toward the elbow. In both cases, the wrist was off the center of the groove toward one side; this caused some confusion in analyzing the films until it was realized that it was an adjustment for the cast of the wire as it feeds from the contact tube. This points up a difficulty which would be experienced in automatic welding if the wire twisted in the torch, or if the cast of the wire changed significantly.

As noted, the forehand angle was generally less than 15° and did not appear to be too critical. The forehand angle was usually smallest at the bottom of the specimens and increased as the welder progressed up the seam; this indicates a desire on the welder's part to keep his hand at a certain position with respect to his body and let the gun tip do the traveling.

In general, the frequency of oscillation used by these welders was considerably lower than those used by the less experienced welder (Welder No. 1, Table I), under partially restricted conditions (Figures 6 to 9). This difference is more pronounced on first passes, and becomes minimal on the cover passes. In case of the triangular or chevron pattern this difference is not difficult to rationalize. However, the weave pattern should be directly comparable. It could be that the "weave" pattern, under conditions of complete freedom of movement, does have a slight vertical motion superimposed to give it at least a small degree of triangularity or ovality. The vertical travel along the seam (Z' direction) seems to be in discrete steps rather than as a continuous movement. This is inevitable with the triangular or chevron patterns, but seems to occur with the weave pattern as well. This again was a degree of freedom which the less experienced welder (Figures 6-8) did not have.

From observing the craters of the welds deposited by these men, the surface flow pattern suggests that the liquid metal is blown against the sidewall by the arc force. The arc does not appear to have approached so closely to the wall to have caused a great deal of sidewall melting. Arc force has blown the metal over against the wall, a distance of 1/8 in. or so. This can also be inferred by comparing actual fusion lines (Figures 14-16) with the weld groove preparations used, as shown in Figure 1.

III. APPARATUS FOR AUTOMATIC SIMULATION OF MANUAL TECHNIQUES

A. Basic Movements

The first task in simulating the manual welding techniques is to develop a mechanical control mechanism which will provide the oscillation patterns required. This apparatus must have control latitude to allow for variations in weave pattern width for various groove sizes, and must also be able to adjust for different travel speeds and current levels.

Weave patterns can be broken down into several basic movements. Either a translation in the X direction, (see Figure 5 for coordinate definitions) or a rotation about a Z axis (θ) can provide for the transverse weave oscillation to fill a wide groove. Similarly, vertical motions to convert a simple weave pattern to a two-dimensional triangle or chevron pattern can be obtained either by superimposing a translation on the travel speed, or by oscillating about an axis in the X direction (ϕ). Motions in the Y direction (parallel to the electrode axis) are probably not required; at least they were not observed to be part of the manual welder's technique. Also, this motion can be automatically controlled to some extent, by a variation in "electrode stick-out distance," or arc voltage. The experimental machine that was developed provided independent control over most of these, although not necessarily at one time. Parameters which could be varied in a cyclic pattern include translations in the X and Z' directions, and rotations about an X or Z axis (ϕ and θ). The difference, in terms of welding technique, between translations and rotations is not significant unless the center of rotation is down close enough to the arc that an appreciable angular rotation occurs. These movements were obtained by mounting the torch as pictured in Figure 4, the same mount as used for the semifree manual welding experiments. A cam-driven oscillator, as pictured in Figure 17, provided the lateral movement (either θ rotation or X movement at any given time). The ϕ rotation was obtained through a third cam, pictured in the later, more complex set-up of Figure 18. The lateral rotations, X or θ, resulted from the cams pushing a cam follower in the X direction (Figure 17). Forehand (ϕ) rotation was obtained via a lever arrangement which followed a cam at right angles to the previous cam; the "ϕ cam" pushed this lever (the channel piece in Figure 18) in the Y direction. Y oscillations of this lever around an X axis cause an oscillation in ϕ.

Z' movements (travel speed) were controlled by a conventional travel speed drive and were either continuous or stepped. Continuous motion was obtained with a variable-speed drive motor on a Berkeley side carriage unit, mounted in the vertical direction. The plate and hold-down system was counter-balanced so that the vertical drive motor was subjected to little loading. This is pictured in the background of Figure 18. Step motion in the travel direction was obtained by switching another drive motor periodically; the movement was actuated by microswitches on the cam shaft, and could thus be accurately tied into the horizontal oscillation pattern. This arrangement is explained in detail in Appendix A.

The above oscillation and travel controls can provide innumerable patterns for welding. Some typical examples are sketched in Figure 19.

B. Additional Parameters

The manual welder makes use of the parameters at his convenient control. However, there are definite limitations on his latitude. For example, if he were to make θ movements around a very close center of rotation, he could drastically alter the angle of incidence between electrode

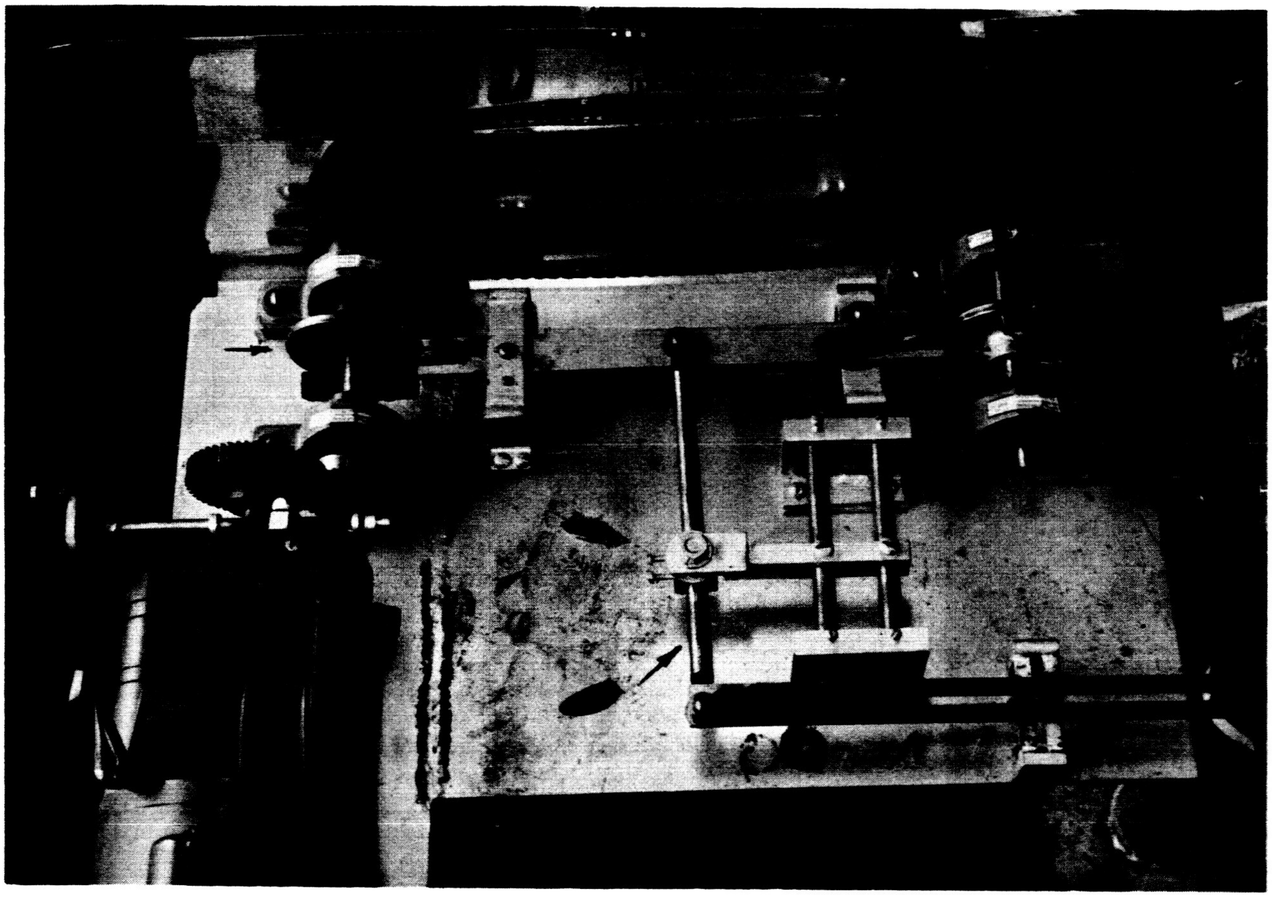


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FIG. 17 - DRIVE SYSTEM FOR AUTOMATIC OSCILLATIONS. Cams, lever, and tie rod are indicated. The oscillation frequency is controlled by the variable-speed motor. Amplitude is controlled by position of lever fulcrum. Dwell time (per cent) is controlled by spacing between the two cam followers.

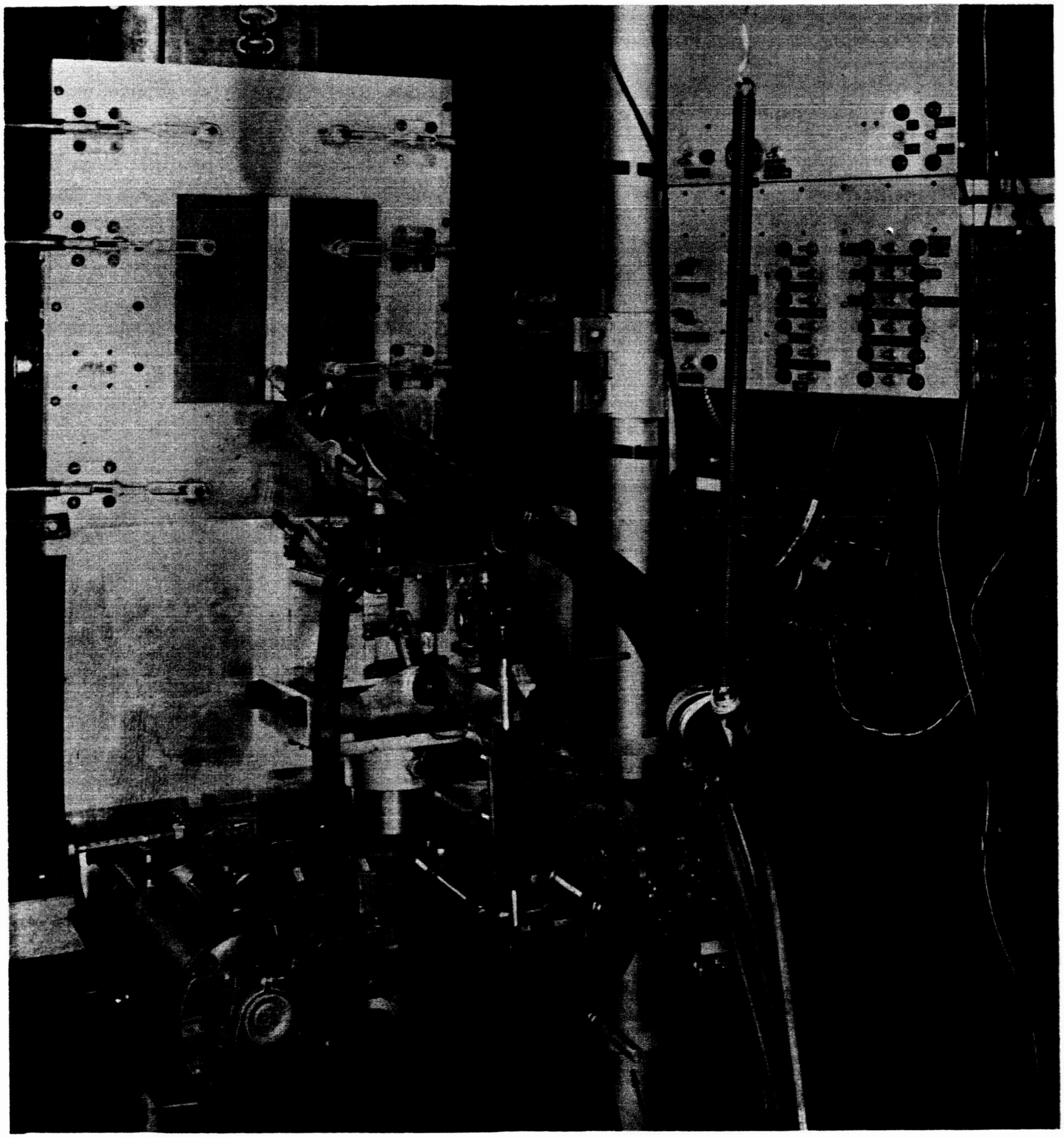

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FIG. 18 - EXPERIMENTAL MODEL OF WIDE-WEAVE VERTICAL WELDING APPARATUS. The vertical oscillation cam (ϕ) and the crank for adjusting the placement of the lever fulcrum (amplitude of θ) are indicated.

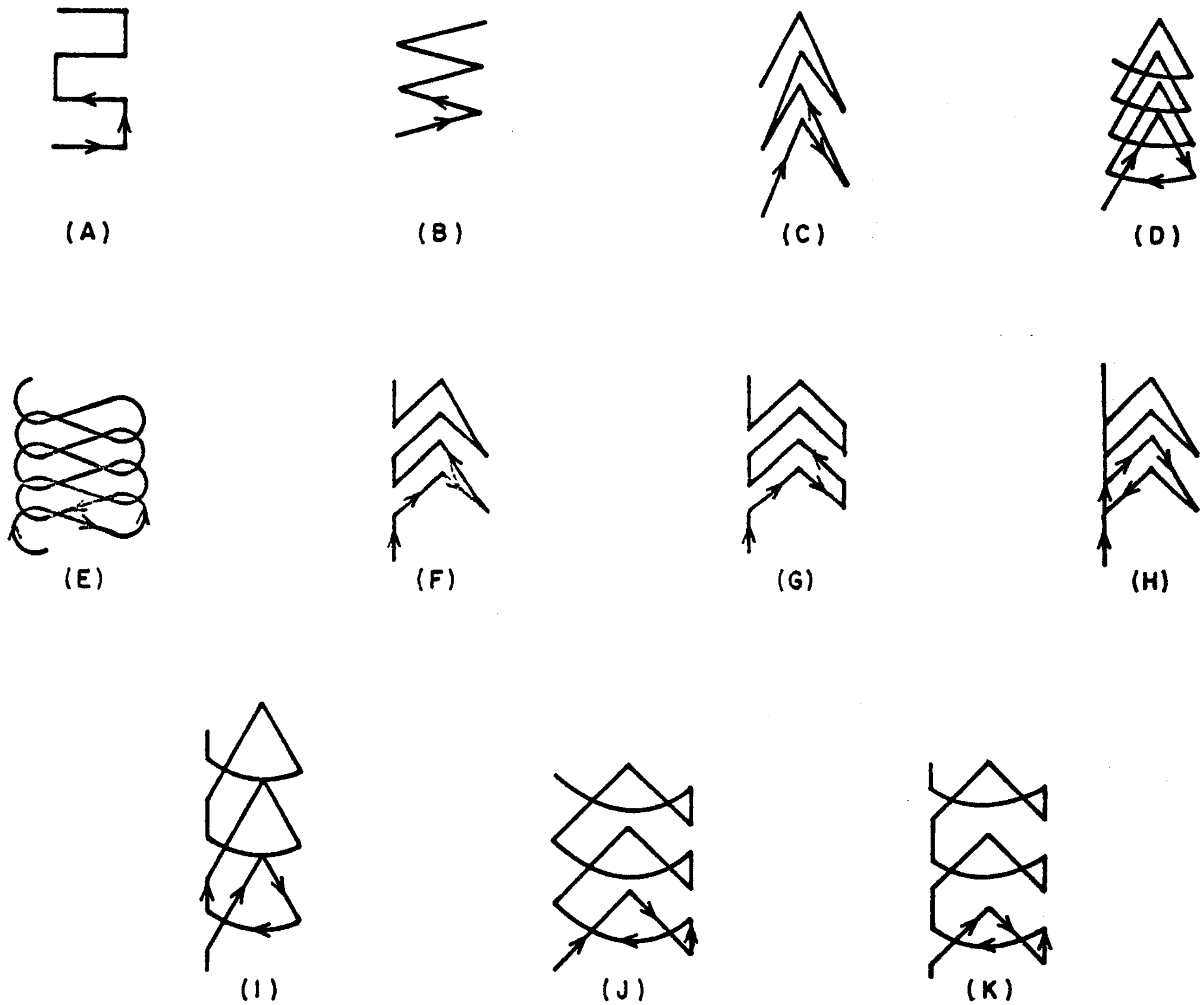

FIG. 19 - EXAMPLES OF SOME OF THE WEAVE PATTERNS OBTAINABLE WITH THE MODIFIED APPARATUS.

wire (the direction of arc force) and sidewall of the groove. Most welders recognize that this is an improvement over a "straight-in" technique, since by increasing the incidence angle the arc force does not tend to wash the liquid metal away from the sidewall, but can be used to push it over to the wall. However, with the rather cumbersome MIG welding gun, and with the stiff wires and leads attached to it, such a movement would be very tiring, if it were possible at all. Therefore, he learns to perform the weld with a large center of rotation as pointed out in the discussion of observations of manual welds (Section II-B). A fully mechanized unit, with more power and more precise control, might provide a short radius oscillation and give appreciably more latitude to an automatic process than a comparable manual process would enjoy. Several mechanisms were considered to provide this motion. This experience is discussed in Section V-B.

Other parameters which might be of assistance to the welding operation, but which are not conveniently available to the manual operator with present equipment, are short-term adjustments of welding current and welding voltage. Arc force is known to be dependent on these parameters, and since it plays an important part in the placement of liquid metal for avoiding undercut and cold-lap flaws, their control may be of some benefit. The electrical parameter control necessary to cause a desired influence on puddle geometry must be on the same order of periodicity as the mechanical weave pattern itself. This means that wire feed--which controls arc current--must vary cyclically with a period corresponding to one or two times the oscillation frequency. Similarly, arc voltage--which is controlled by the power output of the welding machine--should be controlled cyclically with a similar period. The mechanisms designed to provide control over these parameters are described in Section V-D.

IV. AUTOMATIC WELDING EXPERIMENTS

A. Typical Welding Results

The first attempt at automatic vertical weave bead welding was an imitation of the simplest technique observed by the skilled manual welders. A welder was asked to deposit metal in the bottom of the 90° V-groove shown in Figure 1c at the rate of 6 ipm and with a current of 170 amps. The welder was given freedom over ϕ (forehand-backhand angle) and θ (lateral oscillation) movements. He attempted to weave at a rate of approximately 70 cpm, which was the frequency considered necessary to deposit a satisfactory weld bead. He was unable to maintain this deposition rate; the weld metal got out of control and collected in heavy areas leaving undercut at the sidewall. The comparable experiment with the machine weld, using the apparatus shown in Figure 18, was quite successful. The technique was a linear weave motion with a controlled amount of dwell at each extreme of the weave oscillation pattern. A first-pass weld typical of those obtained with this machine technique is pictured in Figure 20. The monitoring oscillograph traces describing the important parameters for the weld of Figure 20 are pictured in Figure 21. The θ oscillation pattern is seen to repeat at the rate of 81 cycles per minute. The amplitude of oscillation was 0.767 in. The higher frequency of oscillation for this weld, as compared to the above manual weld, was necessitated by the slightly higher travel speed, 7 1/8 ipm as opposed to approximately 6 ipm performed by the welder. This higher speed added to the challenge for the machine. This weld shows interesting current and voltage traces which will be commented on later. The radiograph of this specimen revealed only one pore in 10 in. of weld, neglecting a higher porosity rate which was observed at the starting end. Some typical first-pass welding parameter and radiography results are summarized in Table II. The parameter variations tabulated include adjustments in ϕ, travel speed, and amplitude of θ. On the basis of X-ray results, little can be concluded to favor one parameter combination over another. Specimen 838, which has porosity, differs primarily in having a somewhat higher current. Specimen 841, also showing somewhat greater porosity count, differs by having a narrower amplitude of θ oscillation, and a greater forehand angle ($\phi = 21\ 1/2°$). A similar specimen, No. 840, showed a clear X-ray when a slightly increased travel speed was used. Finally, Specimen 803 shows scattered porosity, which is apparently caused by the decrease of forehand angle (ϕ) to zero degrees. Further specimens made with the torch at approximately 2° backhand ($\phi = -2°$) had severe undercut as well as porosity. Figures 22 and 23 show first and second pass welds, respectively; cross sections of these beads are pictured in Figure 24. The slight depression at the sidewalls of the

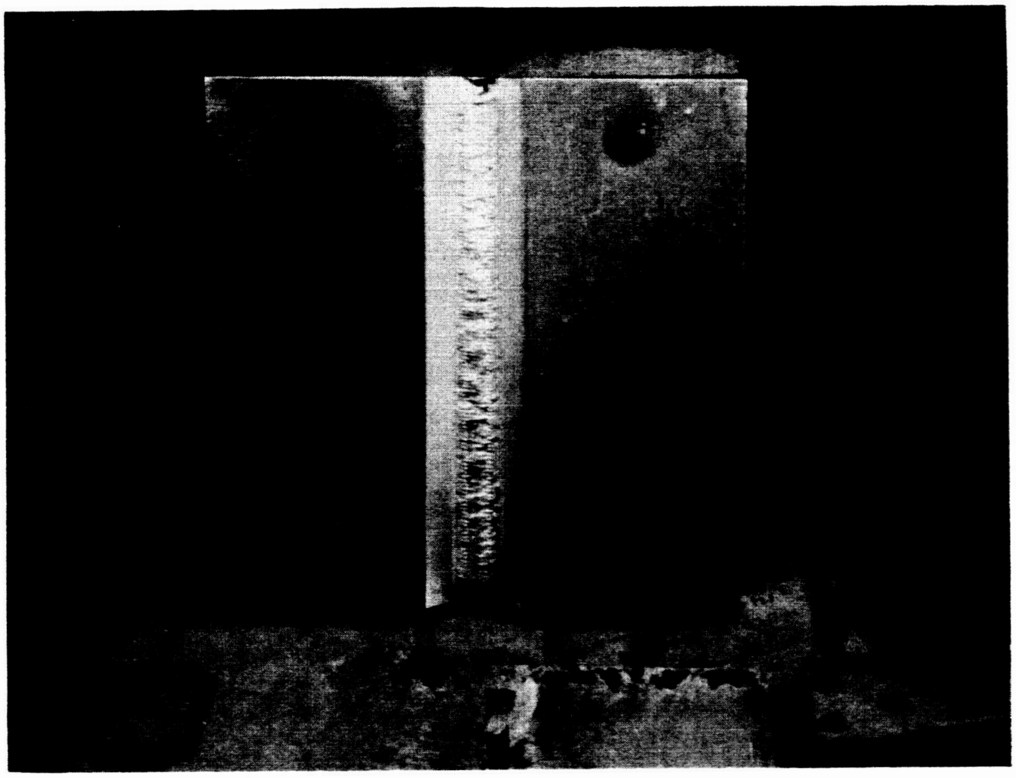

FIG. 20 - FIRST PASS OF WELD IN 1-INCH ALUMINUM PLATE.

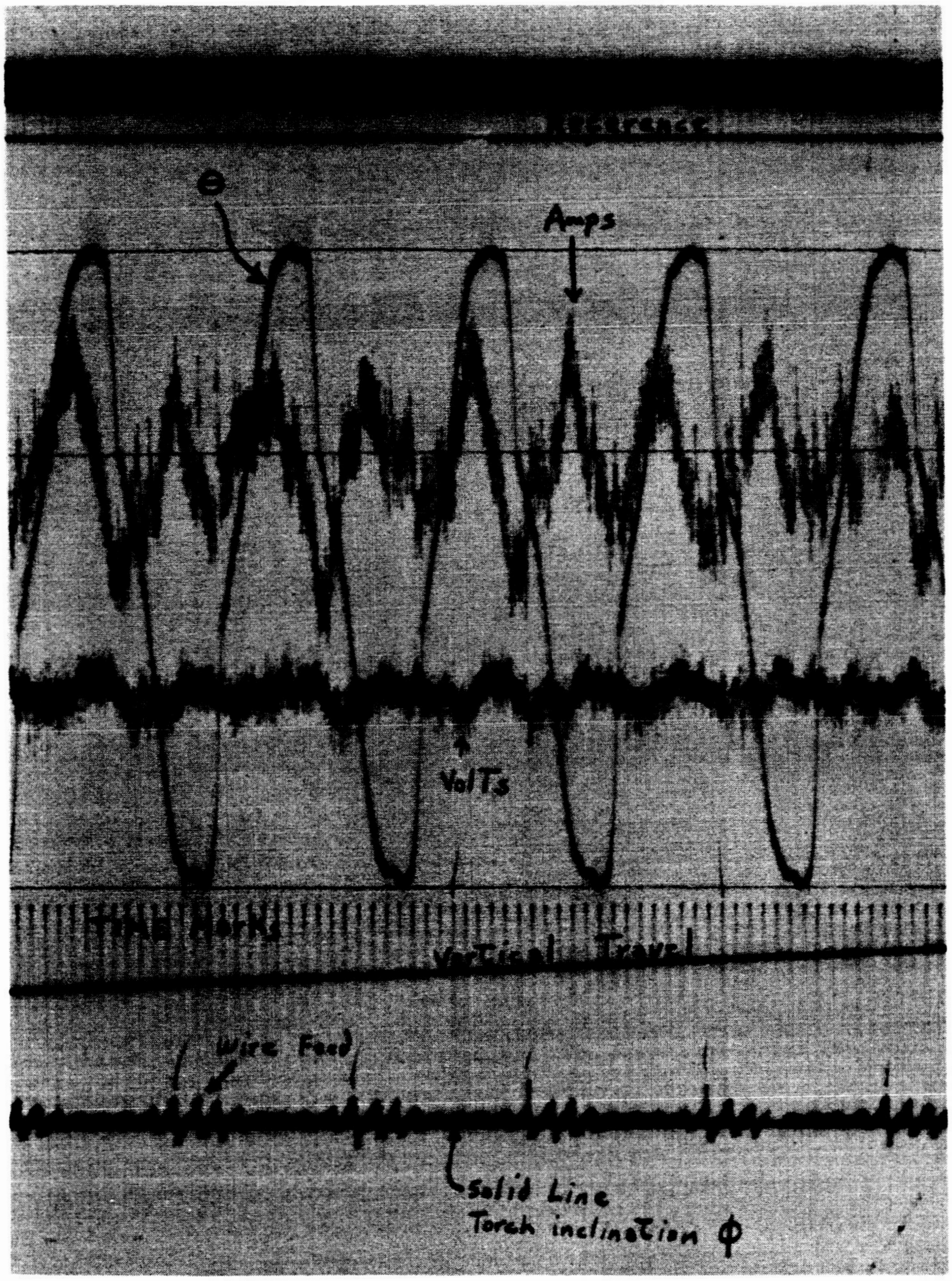

FIG. 21 - OSCILLOGRAPH RECORD OF FIRST-PASS WELD

Amplitude of θ (side-to-side weave width at wire tip)	= 0.767 in.
Frequency of θ	= 81 cpm
φ (torch inclination forehand)	= ~15°
Vertical travel speed	= 7 1/8 ipm
Voltage	= $17.2^{+3.2}_{-2.7}$
Amperage	= 185^{+65}_{-54}
Wire feed speed (3/64 diam.)	= 392 ipm

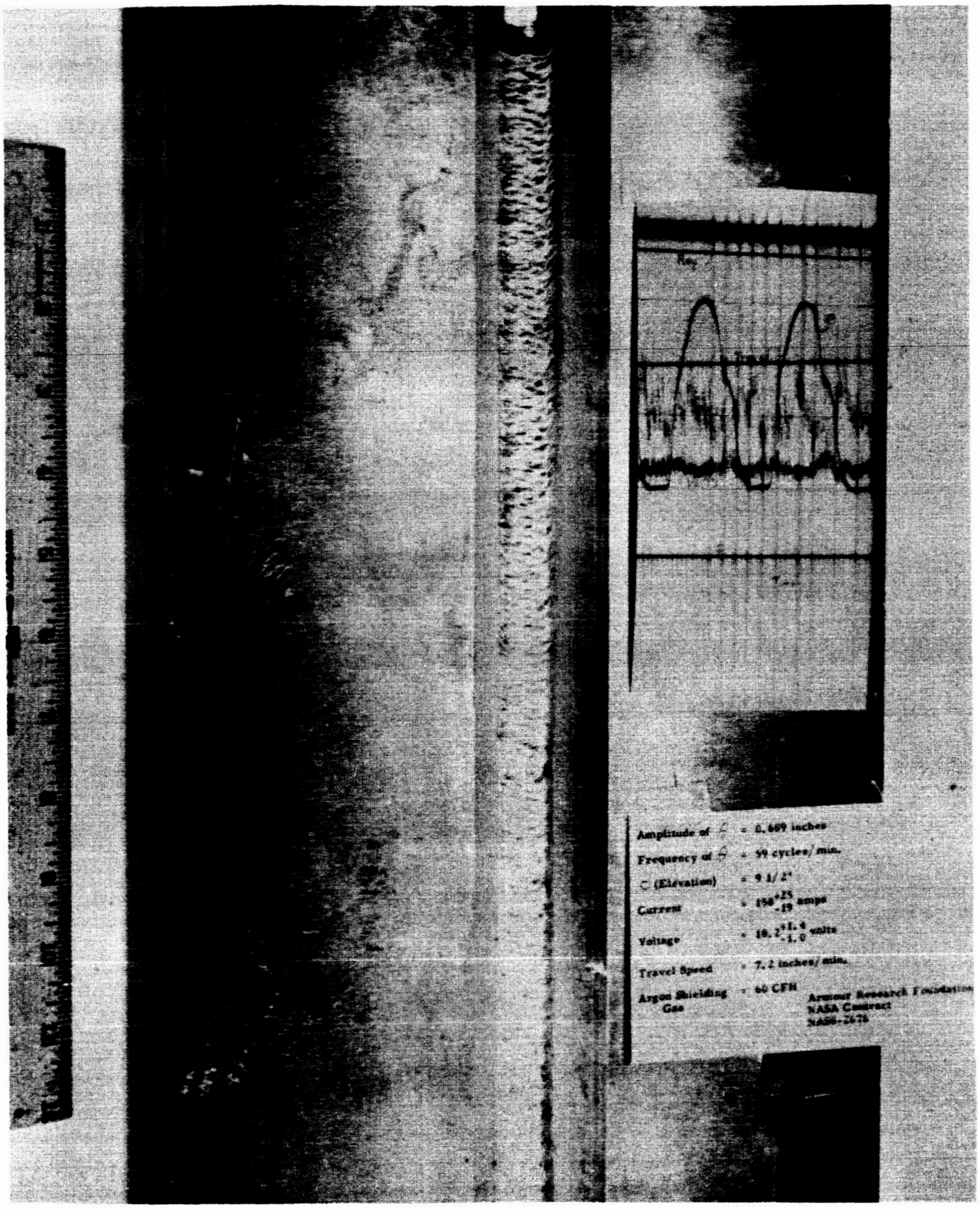

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FIG. 22 - FIRST PASS OF WELDS IN 1-INCH ALUMINUM PLATE.

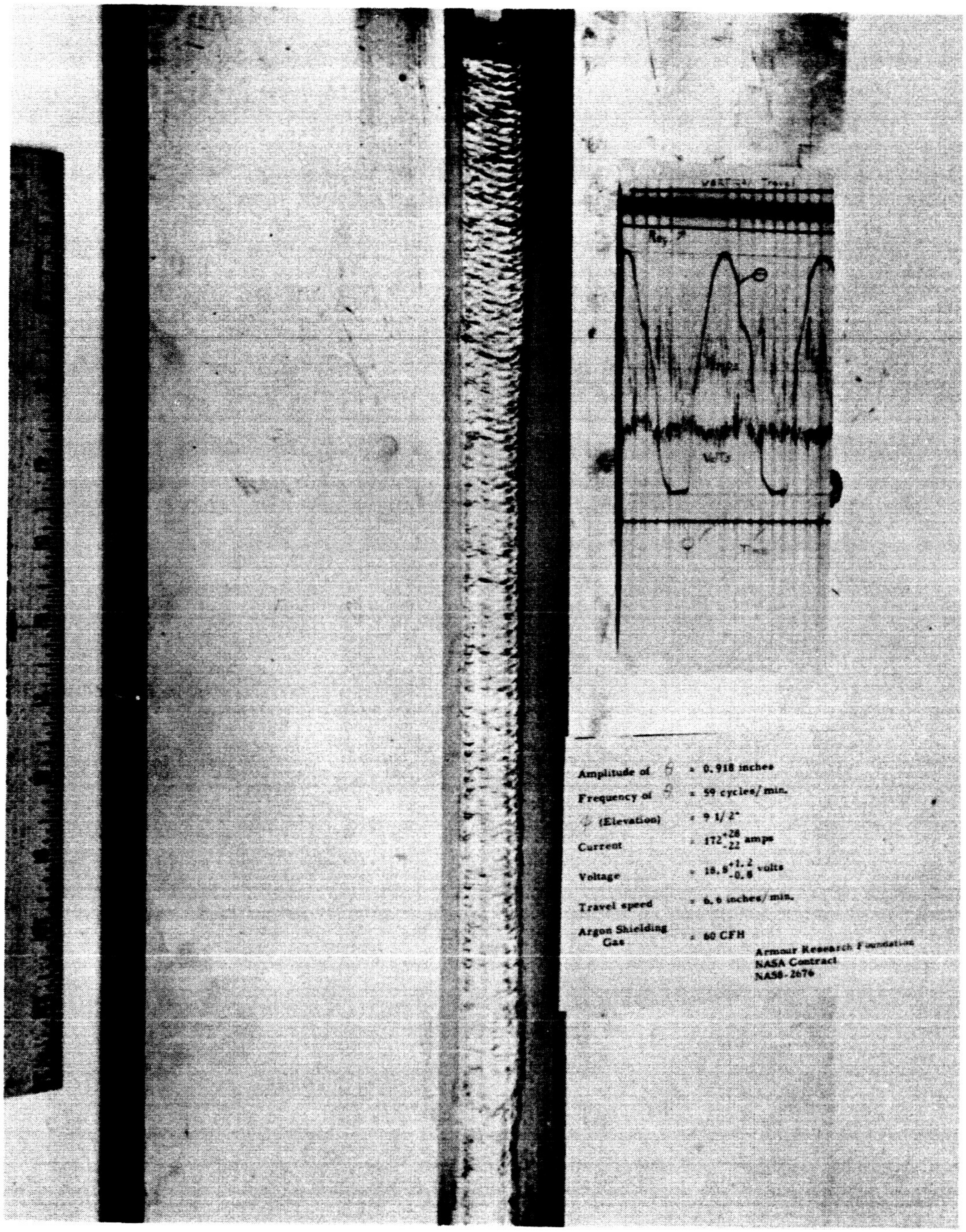

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FIG. 23 - SECOND PASS OF WELDS IN 1-INCH ALUMINUM PLATE.

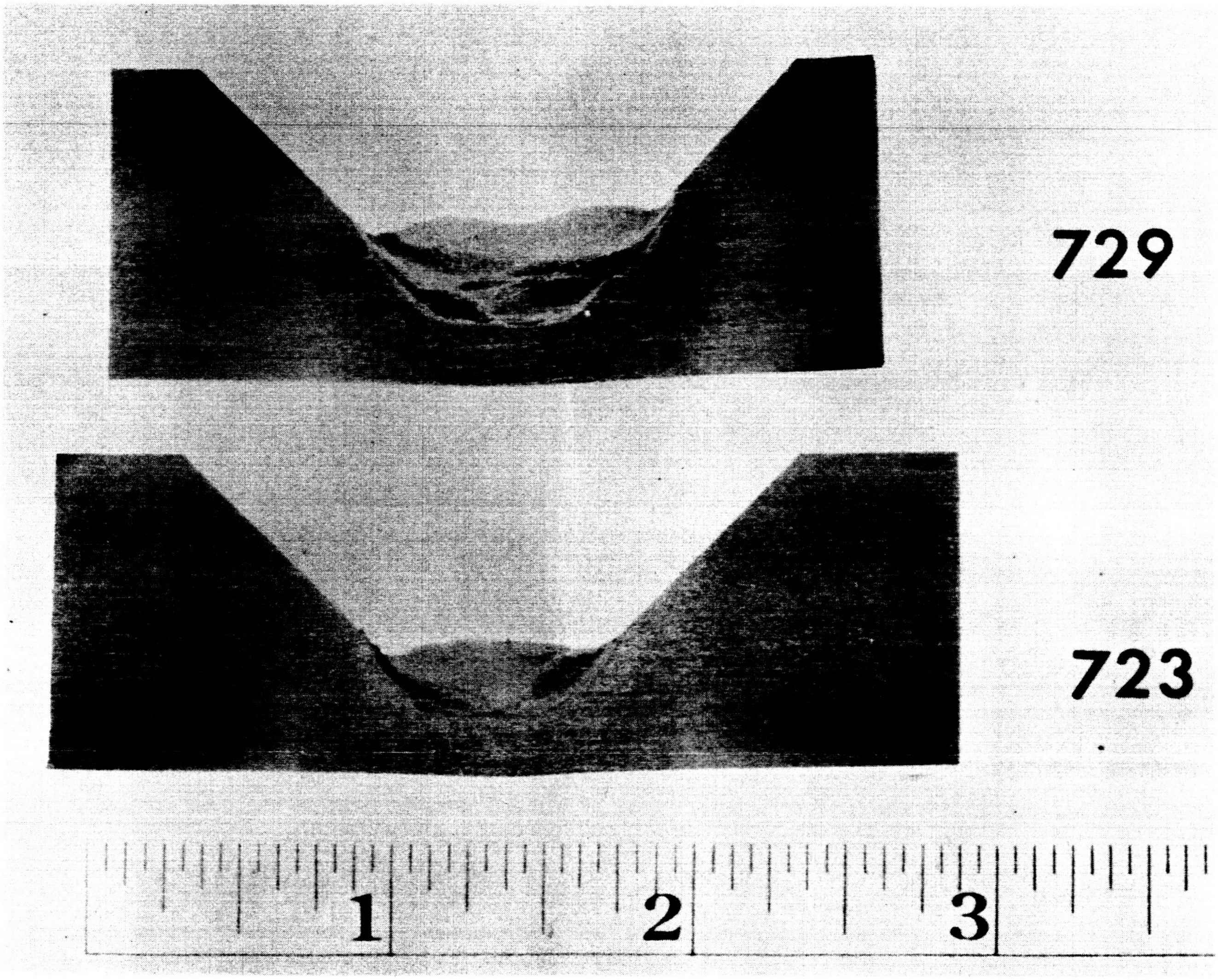

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FIG. 24 - CROSS SECTIONS OF FIRST-PASS AND SECOND-PASS WELDS (See Figures 22 and 23.)

TABLE II

RADIOGAPHIC RESULTS OF

5456 ALUMINUM ALLOY AUTOMATIC WELDMENTS

Specimen No.	Amplitude of θ*, in.	Amplitude of X, in.	Frequency of θ or X, cpm	ϕ, degrees	Vertical Travel Speed, ipm	Avg. Volts	Avg. Amps	X-Ray Results[a]
828	0.767	0	81	14 1/2	6.84	16.9	180	1 pore
832	0.767	0	81	14 1/2	7.14	17.2	182	Clear
833	0.767	0	81	14 1/2	7.14	17.2	185	1 pore
838	0.767	0	81	14 1/2	6.84	17.4	191	(b)
841	0.702	0	81	21 1/2	6.97	17.4	175	(c)
853	0	0.562	81	11 1/2	~7	17.2	169	Clear
840	0.702	0	81	21 1/2	7.14	17.2	173	Clear
803	0.518	0	80	0	6.49	17.9	167	Scattered porosity

* Radius of rotation was 14 in. unless indicated otherwise, measured at wire tip.

(a) Starting porosity was present in all cases.

(b) One region 3 in. long contained scattered porosity.

(c) One area about 1 in. in diameter contained numerous pores.

first-pass weld, and also of the second-pass weld, is probably caused by the slight reduction in amplitude of θ as compared with previous trials. The frequency of oscillation was also somewhat reduced, and travel speed was slightly increased. This accounts for the slightly rougher bead surface texture of Figure 22 as compared with Figure 20. As indicated, it was necessary to slow the travel speed because of the wider oscillation distance for the second pass. The cross section of the two-pass weld, Figure 24, illustrates the start of a difficulty which was to get more critical as the number of passes increased. This is the hollow which develops at the bead center line. Its cause can be rationalized by considering the pattern of oscillation which was used, as shown by the θ trace of Figure 21. With periodic dwell near the sidewalls, which is necessary to provide satisfactory sidewall fusion, and a linear motion across the bead, more metal is deposited near the edges than in the center. This imbalance is erased when the width of the weld is sufficiently small to allow liquid metal to flow from the near-edges to the center. However, with wide oscillations this flow cannot balance the weld. A correction of this difficulty, still with only a lateral oscillation, would evidently be to provide a nonlinear motion which incorporates a hesitation or reduction in velocity after the arc is pulled suddenly away from the sidewall. Possibly the chevron and triangular patterns used by the one skilled welder as described above, is a partial solution to this difficulty. The pattern shown in Figure 25 approximates the suggested change in θ movement; it exhibits a dwell near the centerline after a sudden approach to and retraction from the sidewalls. This particular motion was obtained by taking advantage of play in the system, but cams were later cut to provide a similar pattern. This adjustment was in the right direction, and was successful in avoiding the problem with wider beads than that shown in Figure 24. However, when the width approached ~1 1/2 in., even this improved trace pattern was insufficient to eliminate the centerline depression.

Attempts to simulate the most promising manual technique, that of using the triangular or chevron weave pattern, were not successful in the few attempts made. This lack of success cannot be considered conclusive, since the complexity of developing these patterns in actual welding

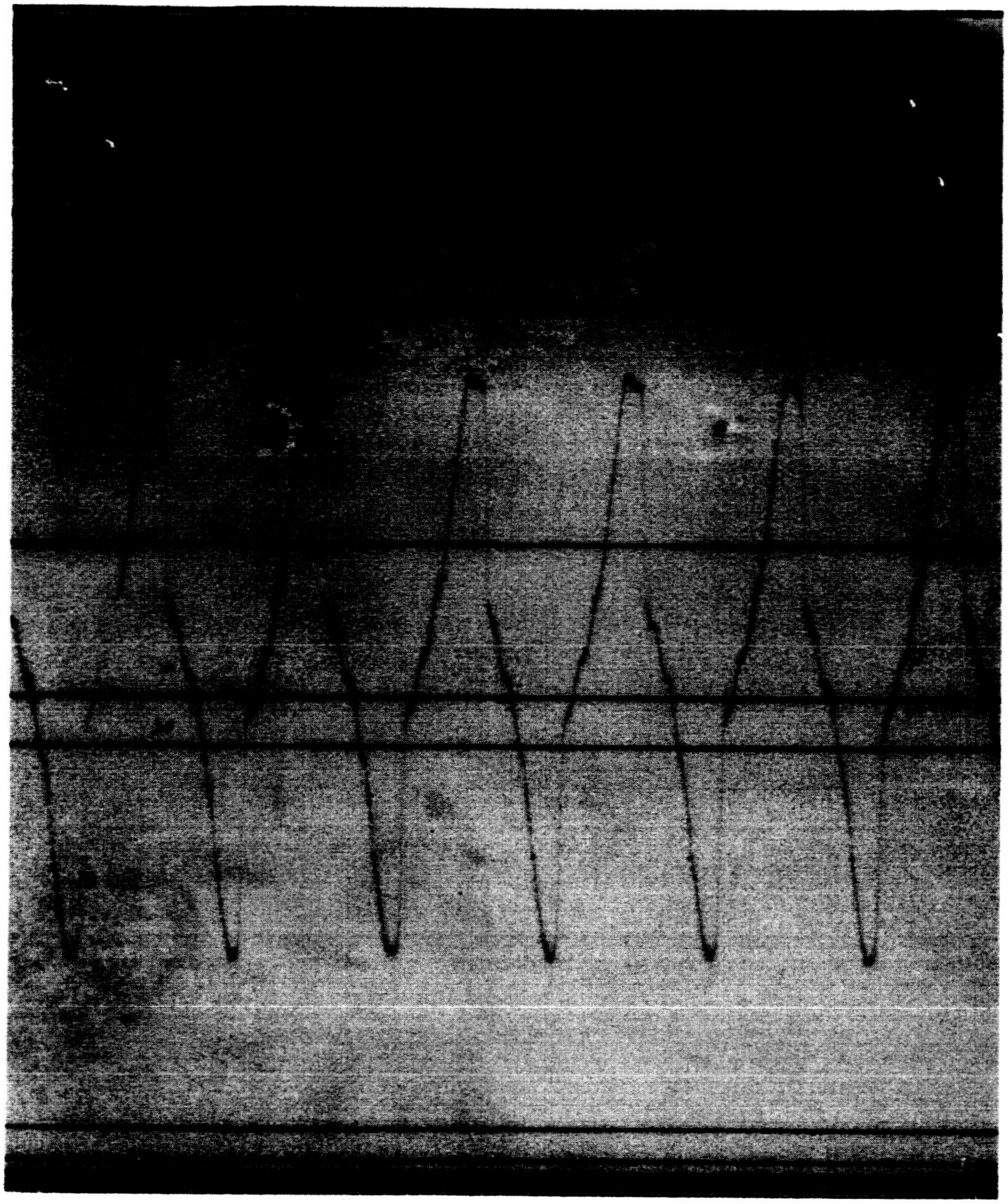


FIG. 25 - RECORDING OF "θ" MOVEMENT AT 80 CYCLES PER MINUTE WITH MINIMUM DWELL.

conditions precluded an accurate evaluation on the existing program. Traces of one attempt are shown in Figure 26. Because of the complexity of this two-dimensional weave approach, and in spite of its potentially greater ultimate advantage, further work was centered on improvement of the demonstration and use of simple weave patterns for the three different joint designs shown in Figure 1. This development can best be presented by describing typical defects and analyzing their causes.

B. Typical Defects

It is easier to understand the capabilities and limitations of the welding process if the cause and cure of typical deficiencies is understood. One category of gross defects is deviations in the bead surface ripple pattern. It is necessary to establish an optimum relationship between the number of oscillations and the distance moved in a given period of time. If the oscillation frequency is too slow with respect to the travel speed, the distance between deposition layers becomes too great and the bead surface becomes rough; in the extreme case, a space develops between successive ripples. An example of this extreme is pictured in Figure 27a. Here the spacing between the ripples is so great that they are not fused to each other. A less extreme example of a high ratio of travel speed to oscillation frequency is pictured in Figure 27b. Here the manifestation is merely a rough surface which is probably only an esthetic disadvantage if present on a cover bead. However, as an intermediate bead, the surface roughness--particularly the depressions between ripple valleys and sidewall--presents areas where insufficient-fusion flaws could occur as subsequent beads are deposited. A subsequent bead, deposited under optimum conditions, could overcome this drawback, but the ripple would tend to make welding more critical.

If low oscillation frequency is combined with excessive heat or excessive deposited metal volume, the puddle size becomes too large for adequate control and the "ropy" pattern pictured in Figure 10 is encountered. This defect is typical of that obtained in manual welding when the operator has difficulty maintaining a preset travel speed. The optimization of the ratio of travel speed to oscillation frequency is dependent on the bead width. As the bead becomes wider, the oscillation amplitude increases and the required frequency for a given travel speed may impose linear

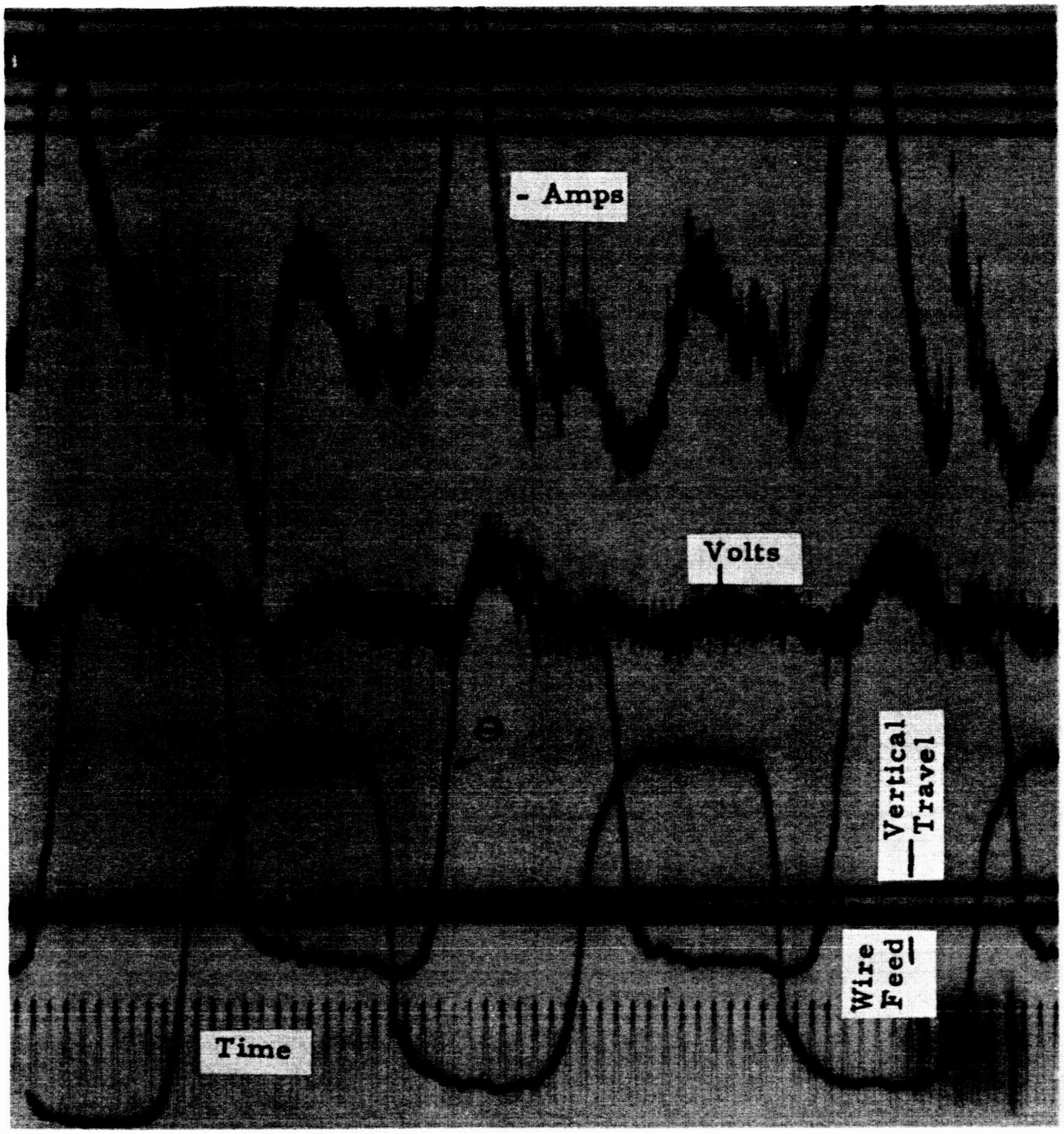
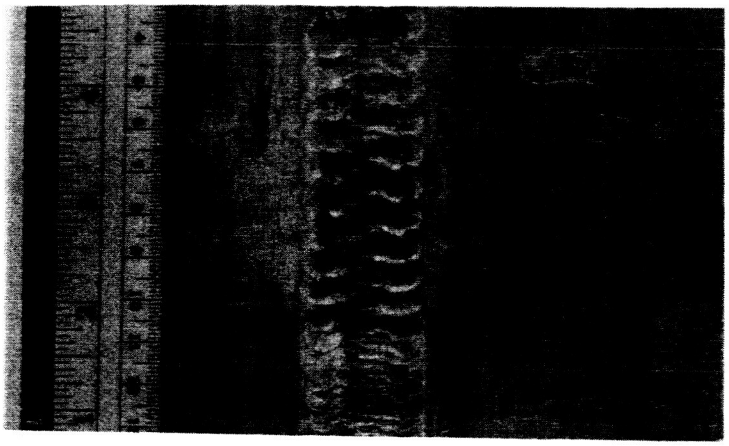


FIG. 26 - RECORDING OF TWO-DIMENSIONAL WEAVE PATTERN.



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(b) Surface is Rough

FIG. 27 - SURFACES RESULTING FROM EXCESSIVE TRAVEL PER OSCILLATION.

travel speeds across the bead which are too great for satisfactory deposition. An example of this is the final pass of the weld pictured in Figure 28. For a given bead width there is a maximum travel speed which can be used; this maximum will decrease as the bead width increases.

Undercut occurs when the force of the arc blows liquid metal away from the sidewall; it is accentuated when the angle of incidence between the arc and the sidewall is quite low or has a backhand component, and when the arc approaches the wall too closely. The optimum situation is when the arc approaches the sidewall just near enough to supply the necessary heat to allow fusion to occur with the liquid metal; the liquid metal is then blown toward the sidewall by arc force under the influence of gravity. When conditions are correct, some liquid metal wets or flows up the sidewall. The arc pressure conditions which cause undercut are aggravated by high currents. Probably the most important welding parameters to limit undercut are those which affect the distance of minimum approach of arc to wall; amplitude of oscillation (θ) or centering of the bead accurately in the groove. The approach of the arc to the sidewall is more critical as the base metal plate temperature increases, and as the angle of incidence is decreased by going to a groove with decreased included angle. Thus the defect is of prime concern in welding 20° U-grooves, but is seldom encountered in welding 90° V-grooves. Figure 29 shows an example of this flaw.

A family of defects can occur when the solid metal to which the liquid is being fused is not sufficiently hot for proper wetting and fusion. These defects, depending on their geometry and placement within the weld, are variously called cold shuts, cold laps, or lack of fusion. Perhaps the most prevalent location of lack-of-fusion is at the corner between the root, or surface of the previous bead, and the sidewall (as shown in Figure 30a). This corner, being farther from the arc, is sometimes difficult to heat adequately. In some instances, again accentuated by joints of small groove angle, the arc actually skips from the root to the sidewall, bypassing the corner itself, as it approaches the sidewall. The probability of arc skipping is increased by increasing the arc length. Thus practically all the welding reported herein was performed with relatively short, low-voltage arcs. Increased arc force, caused by increasing the current

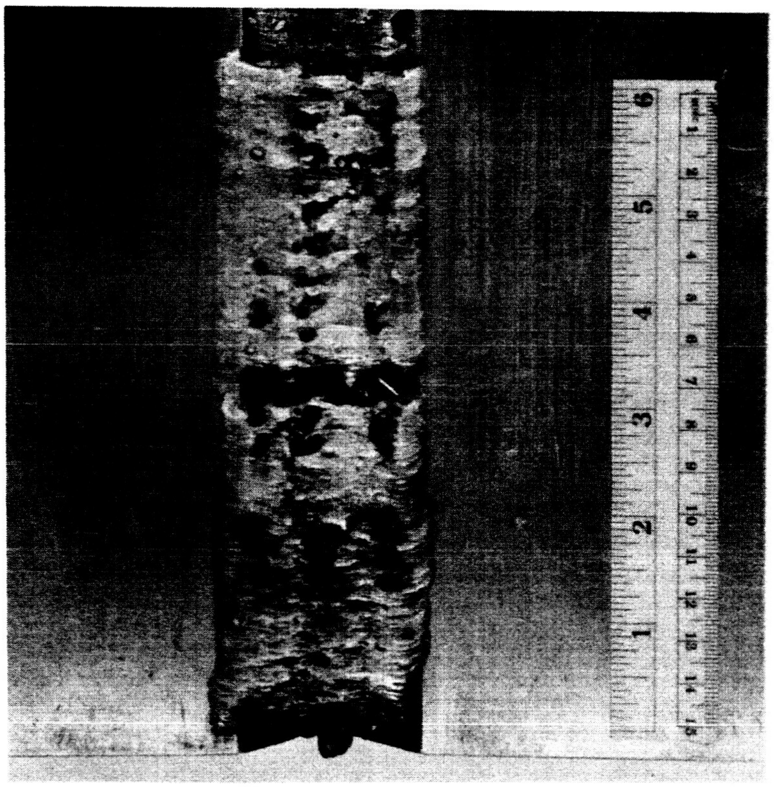

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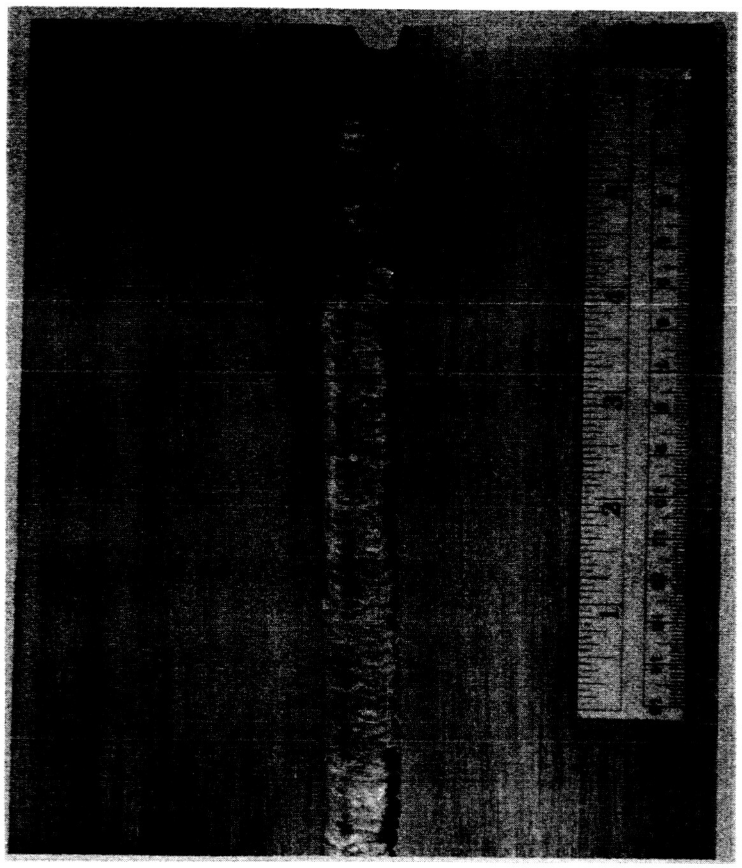
FIG. 28 - SURFACE RESULTING FROM EXCESSIVE TRANSVERSE SPEED.

Neg. No. 25245

(a) Undercut and Poor Fusion



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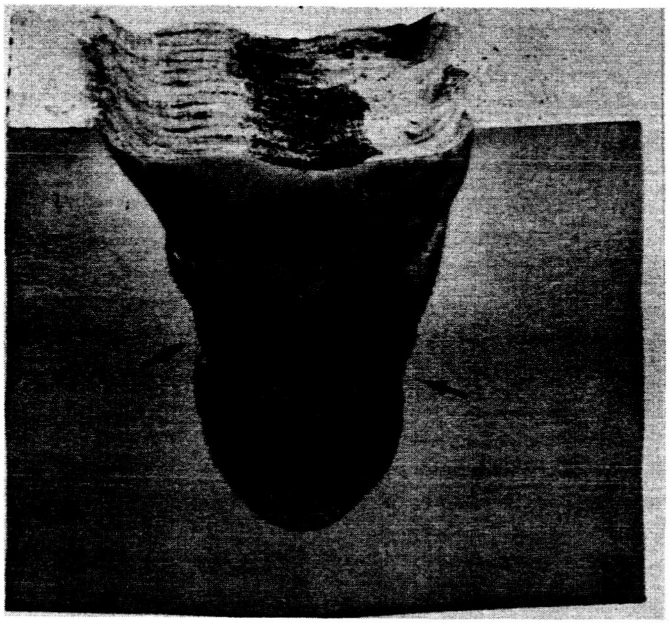
(b) Undercut on Right Side

FIG. 29 - TYPICAL UNDERCUT.



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(a) Poor Corner Fusion

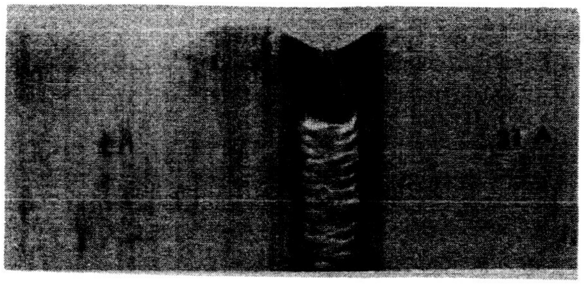
Neg. No. 23999

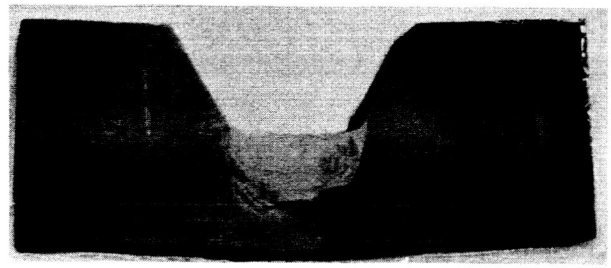
(b) Cold Lap

FIG. 30 - TYPICAL COLD WELD METAL DEFECTS.

density in the electrode wire, would tend to prevent arc skipping, but this imposes the risk of undercut, which is augmented by high arc force. The elimination of poor corner fusion is an incentive for developing a system of oscillation around a short radius. This would effectively increase the angle of incidence, for a given groove opening angle, and would therefore greatly reduce this problem.

A similar defect is "cold lap," pictured in Figure 30b. In this weld the liquid metal did not wet the solid surface of the previous weld bead. This probably resulted from insufficient removal (arc cleaning) of the heavily oxidized weld surface. A similar defect, shown at the bottom of the cross section of Figure 29a, occurs when liquid metal comes in contact with cold solid metal. This might result from pushing the puddle, by arc or gravity forces, to cold metal. It is caused by deviations in welding parameters similar to those which cause the "ropy" surface shown in Figure 10. If the volume of liquid metal becomes too great, it rolls away from the arc, and down onto metal which is away from the arc heat source. Other defects have to do with the geometry of the bead at the sidewall. This geometry is of importance primarily because it influences the ability to deposit subsequent beads without flaws. An ideal bead cross section has a uniformly concave surface near the sidewall, as pictured in Figure 31a. (This section has other flaws; only the surface is "ideal.") An exaggerated example of very poor side-wall geometry is shown in Figure 31c, with the intermediate cross section, satisfactory in most respects, pictured in 31b. Probably the most important machine parameter in controlling this geometry is again the approach of the arc to the sidewall. The bead of Figure 31c was formed by a procedure which did not direct arc heat to the sidewall, but did deposit appreciable metal. Had this metal been pushed over against the sidewall, a weld similar to that shown in Figure 29a or 30a may have resulted. The angle of incidence between the electrode and the sidewall plays a role in bead geometry. The ideal geometry could not be obtained with a 20° U-groove because of the low angle of incidence. Figure 32a illustrates about the best that could be obtained with ideal amplitudes of oscillation. If an attempt is made, with a 20° groove, to eliminate this sidewall corner and obtain a concave bead as pictured in





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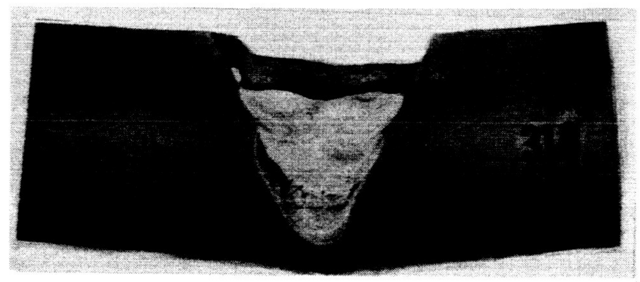
(a) Ideal Bead Surface



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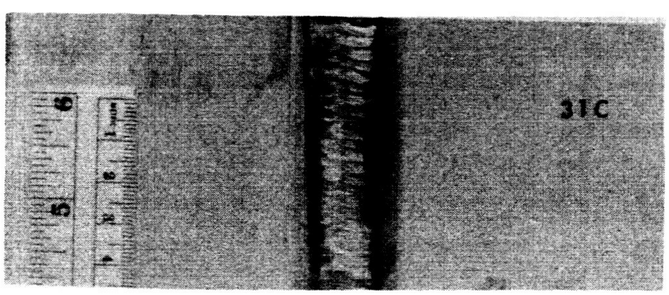
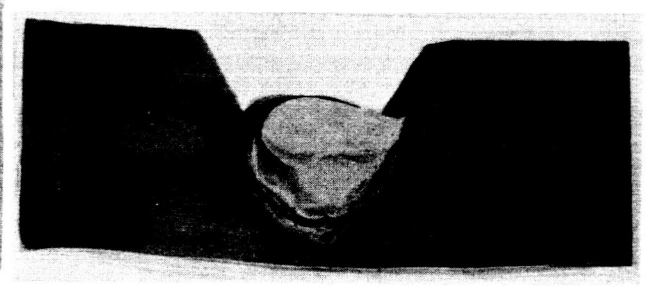
(b) Acceptable Bead Surface





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(c) Convex Bead Surface

FIG. 31 - BEAD CROSS SECTIONS WITH 60° V-GROOVE.

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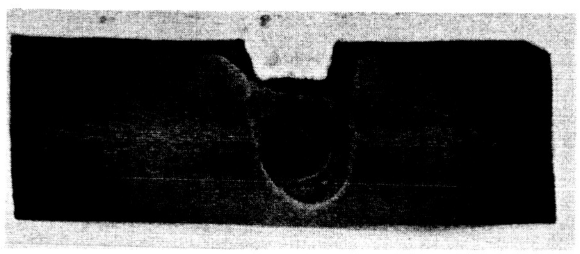
(a) Best Surface Obtained with 20° Groove.



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(b) Arc Skipping (LH) and Convex Wetting Angle.

FIG. 32 - BEAD CROSS SECTIONS WITH 20° U-GROOVE.

Figure 31a, the arc tends to skip to the sidewall giving a melted corner as shown on the left in Figure 32b. Even the manual welders could not obtain the ideal bead surface in this groove, as is shown in Figure 16.

C. Summary of Machine Parameters

To summarize, it could be said that good welds can be produced, either by machine or manually, by merely avoiding these defects. A set-up procedure would be as follows: A welder, would first get an oscillation amplitude which is approximately correct with respect to groove width, after adjusting welding current and welding voltage to provide a relatively short arc high in the "drop transfer" current range. Next, the frequency of oscillation and the travel speed would be adjusted in relation to each other to provide a desirable ripple pattern--generally having 8 to 10 or more ripples per inch to avoid the ropy appearance of Figure 10. Adjustment in current level may be required as travel speed is changed. In order to realize the maximum deposition rate, the general approach to these adjustments would be to ease the travel speed to higher and higher values, attempting to adjust oscillation frequencies and current to keep up with these high travel speeds. Sooner or later, depending on bead width, the point will be reached where the transverse travel speed is too great for satisfactory wetting in the center of the bead, as shown in Figure 28. In making these adjustments it will also be necessary to observe the volume of the puddle. If this gets too great, caused by excessive arc current, the puddle will tend to sag causing ropiness or will run over cold solid metal causing cold shuts as shown in Figure 30b. Once the heat and oscillation parameters are adjusted as described, the next step is to control the geometry of the bead at the sidewall, preventing undercut, arc skipping, or excessive convexity. The welder, in working toward the ideal sidewall geometries, will be making fine adjustments in the amplitude of oscillation and possibly in the percentage dwell time controls. On the present machine, oscillation amplitude can be adjusted while the machine is in operation and the weld is being observed. This cannot be done with percentage dwell time, but a suggested modification will allow this adjustment to be made during welding also.

As the weld is being made, the welder will be primarily concerned with keeping the bead on center, which can be done by small adjustments during welding, and possibly in making minor adjustments in oscillation amplitude to account for minor variations in groove width which might occur. In laboratory welding experience it was found that a relatively inexperienced welder could teach himself to set up optimum welding parameters, and to make the fine adjustments necessary during welding.

Some welding procedures developed according to the above guidelines are given in Table III. The welding arc is held approximately constant at 200 amps, 23 v. It is interesting to check these data against logical expectations. For example, oscillations per inch should tend to be constant, or at least have a consistent lower limit; values vary from 7.8 to 12.2. Similarly, horizontal travel speed (resulting from oscillations) should tend toward a maximum value; the range is 43 to over 100 ipm, with unsatisfactory surface appearance at speeds greater than ~120 ipm. Absolute dwell time would be expected to be constant, at least for the non-cover passes. However, this parameter does not appear to become critical until the weld is appreciably wider than the size of the molten puddle. The data indicate that, with oscillation greater than 7/8 in., dwell becomes a decreasing percentage of the over-all oscillation period, and approaches 0.1 sec or less.

The width of oscillation is too critical to establish, in practice, by any means other than trial and error. However, one might expect the difference between oscillation width and groove width (at the arc point on the electrode) to be a "constant," which may require adjustment for variation of arc length, groove angle, and perhaps puddle size. Except for cover pass data, this difference is 1/8 in. for the 20° groove, 3/32 to 9/32 in. (increasing as pass number increases) for the 60° groove, and ~1/8 to 7/16 in. for the 90° groove (again increasing as pass number increases). The increasing gap between arc and sidewall, as bead width increases suggests that arc force has a more effective sidewise component with wider passes.

TABLE III

WELDING PARAMETERS FOR AUTOMATIC WIDE-WEAVE WELDING

Bead Identification	Weld Travel Speed, ipm	Width of Groove for Pass to Fill, in.	Amplitude of Oscillation, in.	Oscillation Frequency, cpm	Dwell Time % of cycle	Dwell Time sec	Lateral Arc Speed, ipm	Oscillation per Weld, in.
20° Vee, 1st pass	4 1/2	3/8	1/4	45	47	.31	43	10
20° Vee, 2nd pass	6 1/4	1/2	3/8	57	47	.26	80	9.1
20° Vee, 3rd pass	6 1/4	cover	7/16	57	47	.26	94	9.1
60° Vee, 1st pass	4 1/2	15/32	3/8	45	47	.31	64	10
60° Vee, 2nd pass	4 1/2	21/32	7/16	48	47	.29	79	10.7
60° Vee, 3rd pass	6 1/4	29/32	5/8	49	25	.15	82	7.8
60° Vee, 4th pass	4 1/2	cover	7/8	54	10	.11	105	12
90° Vee, 1st pass	6 1/4	11/16	9/16	49	47	.29	104	7.8
90° Vee, 2nd pass	4 1/2	15/16	7/8	54	10	.11	105	12
90° Vee, 3rd pass	4 1/2	1 3/16	15/16	55	5	.05	109	12.2
90° Vee, 4th pass	4 1/2	1 7/16	1	55	5	.05	116	12.2
90° Vee, 5th pass	4 1/2	1 5/8	1 3/16	55	5	.05	137	12.2
90° Vee, 6th pass	3	cover	1 3/8	30	5	.10	87	10

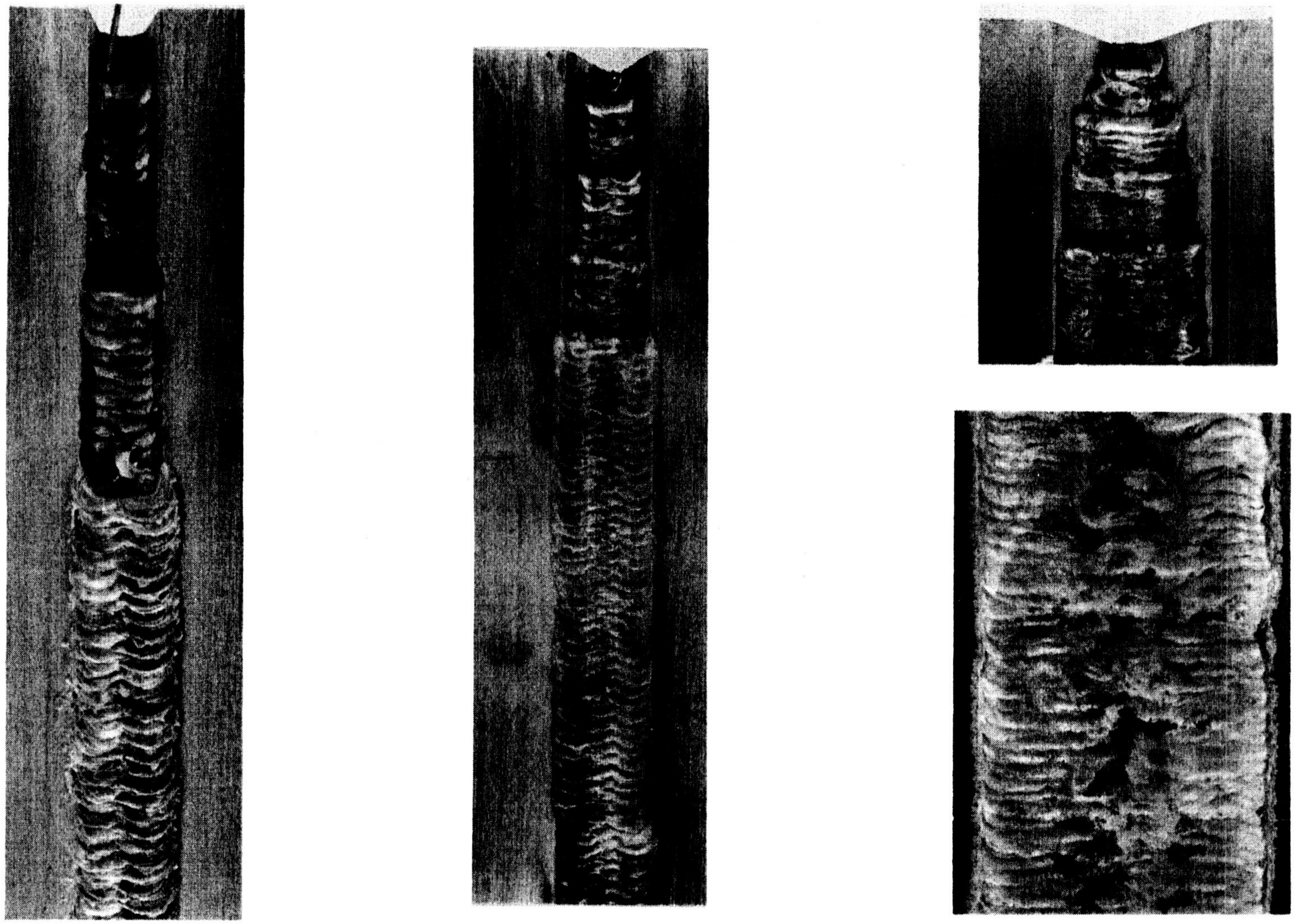
3/64 in. wire, argon shielding gas, 200 amps, 23 volts, 1 in. thick plates with root passes already placed (simulated).

The welds obtained with the settings of Table III are pictured in Figure 33. The fifth pass in the 90° V-groove is unsatisfactory because of defects caused by excessive transverse speed. A parameter adjustment to reduce transverse travel speed gave the improvement shown in pass 6.

D. Weld Groove Design

For each particular defect discussed, it is apparent that groove geometry and oscillation pattern play important roles in the ability to obtain satisfactory welds. For example, as the groove wall gets steeper and steeper, the flaws undercut, arc skipping, and excessive convexity are more difficult to prevent. However, because the groove is narrower, higher travel speeds can be realized because greater oscillation frequencies are possible. As the groove is opened--for example, in the 90° V-groove of Figure 1--the sidewall geometry problems become less critical. Fairly uniform concave corners can be realized, undercut is easier to avoid, and arc skipping is not prevalent. The problems with these wider grooves involve the traverse of the bead. As the width increases, the linear transverse speed for a given oscillation frequency increases to the point where insufficient metal is deposited in the groove center and, in the extreme, where wetting is inadequate in the bead center as shown in Figure 28. The former problem has been greatly mitigated by redesigns in oscillation pattern--requiring a new cam--and could probably be eliminated entirely. Inadequate wetting can also be eliminated but only at the expense of slowing travel speed. Thus as the bead gets wider and wider, the allowable travel speed along the seam becomes lower and lower.

The final compromise on groove angle probably lies somewhere between 20° and 60°. Satisfactory welds were obtained with 20° grooves, but the parameter settings were quite critical and the necessary high reproducibility would be difficult to obtain. A 60° groove, the next opening angle studied, is very satisfactory from the standpoint of welding convenience, but would involve a joint of excessive width if plate thicknesses increased much beyond 1 in. Probably an acceptable compromise would be somewhere around 30°.



20° Groove 60° Groove 90° Groove

FIG. 33 - WELD OBTAINED WITH THE MACHINE PARAMETERS OF TABLE III.

The solution to this dilemma is to obtain the advantages of open grooves, with the inherent large angles of incidence between electrode wire and sidewall, while retaining a narrow bead. This combination can be realized by drastically decreasing the radius of oscillation. Some attempt was made, during the program, to design apparatus which would provide very short radii (on the order of 1 in. or less). However, this effort was curtailed, partly because it was felt that much could be learned with large radii and this knowledge could be readily applied to subsequent experiments with short radii. Also, short radii would involve the additional technical difficulties of moving relatively large masses--the welding torch--over appreciable distances with appreciable accelerations. Also, it was observed that highly skilled manual welders were able to deposit satisfactory narrow-groove welds without resorting to cumbersome short radii oscillations.

V. DISCUSSION OF APPARATUS

A. General Comment

Essentially all of the experimental welding studies were performed with the oscillation apparatus pictured in Figure 18. The detailed design and workings of this apparatus are discussed in Appendix A. This apparatus essentially evolved during experimentation, with features being added as the need arose. This apparatus was very effective for the primary use intended--namely, to learn about automatically controlled weave techniques. It was versatile, yet simple enough to allow for reasonably convenient disassembly and reassembly for changing output characteristics. However, as must be expected of such a development procedure, its performance can be improved by a careful redesign of some of the components and a general tightening of connections. This would allow more precise coordination of actual tip movement with the cam-actuated movement that is fed into the device. Comparing traces of actual movement, as shown in Figures 21, 22, 23, and 25, with the "linear" cam shapes to cause this movement illustrates the lack of precision in the present device. The cams were designed to provide a simple trapezoid shape, or linear motion between flat periods of dwell. One important benefit of an over-all tightening up would be that sufficient control would be obtained to allow profitable experimentation in two-dimensional weave patterns--that is, triangular and chevron patterns or others. The potential advantage of these patterns are not fully investigated in this program and is still a fruitful area for future work.

It might also be of advantage to relocate the axis of ϕ rotation. As the apparatus presently exists, a ϕ rotation also causes a Y movement component which is appreciable ($\sin \phi \doteq 1/4$, so $\Delta Y = 25\% \Delta Z'$). This carries the contact tube away from the work, increasing "stick-out distance," as the forehand angle ϕ is increased for a given setting. This could be eliminated by moving the ϕ axis up above the torch body (in the Z' direction) until $\phi = 0$, that is the axis is on a level with the weld itself. In this manner the torch could still have a forehand angle in the desirable range of 10° to 20°, but ϕ rotation would not drastically change Y movement, particularly if the radius of ϕ rotation were comparable to that presently used--14 in. or so. Two dimensional patterns could then be used without recourse to stepwise travel speed motions.

B. Short Radius Oscillation

Probably the primary mechanical limitation on the existing design philosophy is the inability or difficulty in obtaining relatively high-frequency θ (transverse) oscillations around a short radius of curvature. As pointed out, this characteristic would be desirable because it should allow weave welding of narrower grooves by providing a more favorable vector for arc force. Three mechanical modifications which would have afforded shorter radii oscillations were given brief consideration of this program. One is a trapezoid-level arrangement shown schematically in Figure 34. This arrangement will allow the programming of short radii oscillations without the necessity of placing a mechanical axis of rotation down into or near the weld groove itself. By varying the ratios of the nonparallel arms, any number of radii can be obtained. These oscillations generally involve some movement in the Y direction along with the oscillation; this movement could conceivably be made to assist in the welding operation if proper arms could be found; innumerable possibilities exist with this arrangement. However, the

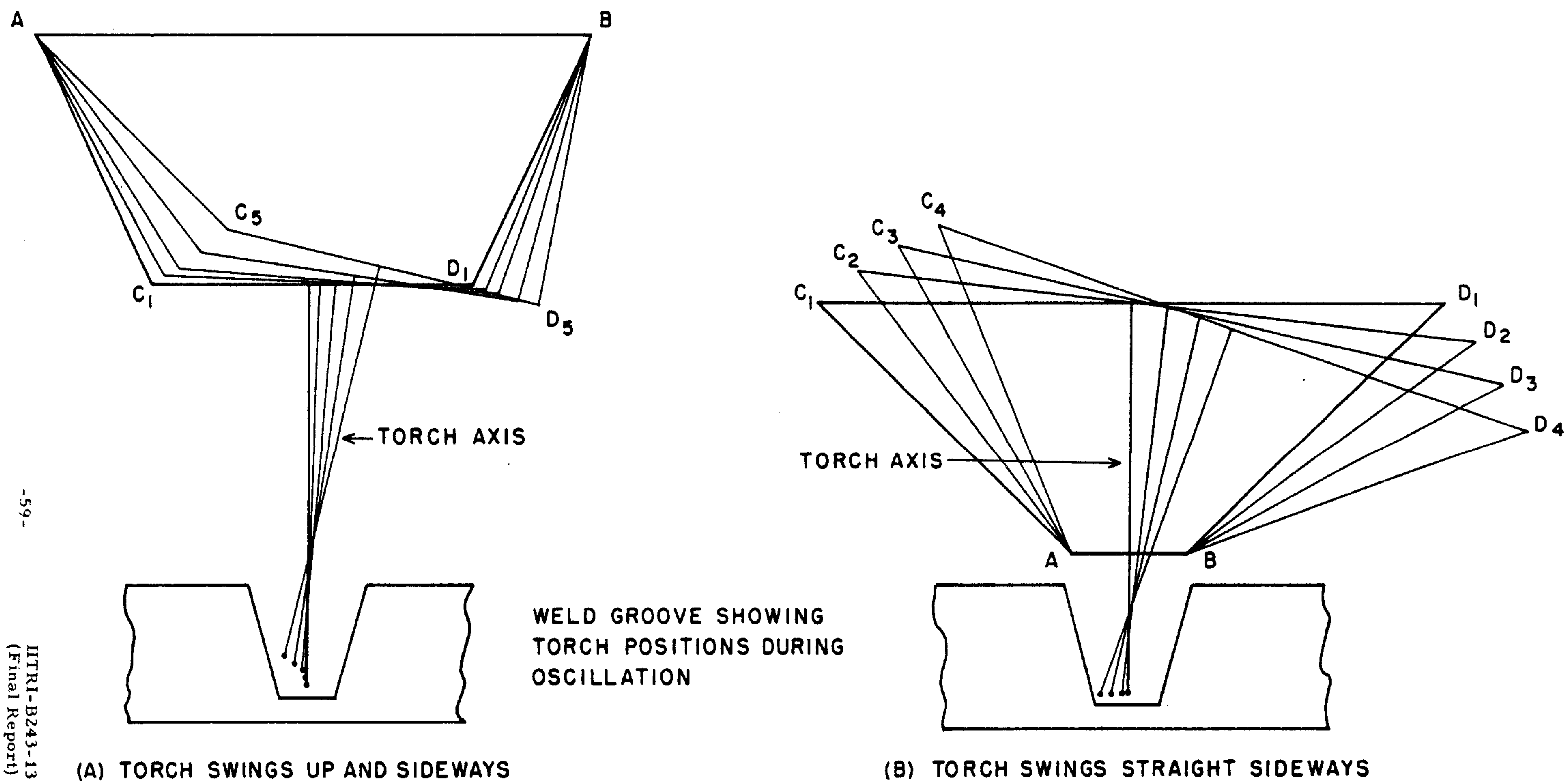
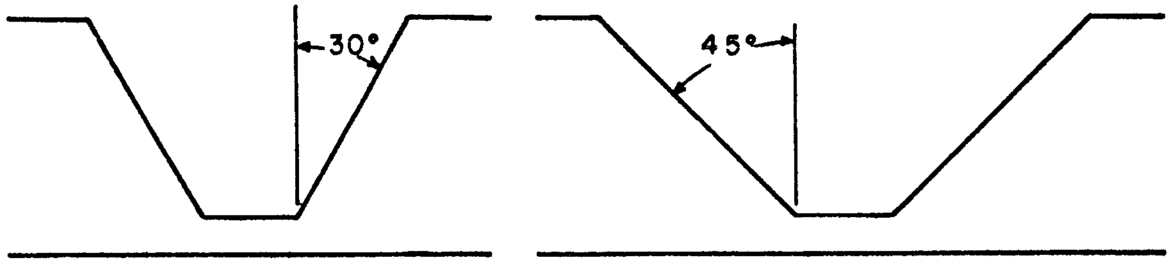


FIG. 34 - TWO SCHEMATIC VERSIONS OF TRAPEZOID SYSTEM FOR OSCILLATING ARC ABOUT SHORT RADIUS.
A more favorable pattern is obtained by placing fixed arm (AB) closer to the arc (b) than the torch platform (CD).
Subscripts 1-5 refer to sequential positions.

difficulty in using an apparatus of this type is that, regardless of how the movement is driven, the mechanical requirements of swinging the large welding torch, with associated stiff cables, is prohibitive. This can be demonstrated by a brief analysis of the angle through which the torch must rotate in order to provide a significant influence on the incidence angle of arc to sidewall. The sketch of Figure 35 illustrates that angles of incidence in welding experiments with 60° and 90° grooves, which have been found ample in both manual and automatic welding experiments, are 30° and 45°, respectively. A sketch of a 20° groove, with the electrode angled sufficiently to provide a 30° angle of incidence, shows that the electrode itself must be 20° from the axis of symmetry. The simple geometrical analysis indicated shows that in order to obtain this angle, the torch must rotate about a point which is approximately 1/2 in. back from the root surface and must rotate through a total angle of 40°. Since the center of gravity of the torch is approximately 14 in. back from this center of rotation, this center of gravity must move approximately 20 in. per cycle of oscillation, or at an average rate (using 1 cps as typical) of approximately 20 in. per second. It is obvious that the accelerations involved in maintaining this oscillation frequency over such a wide arc would be prohibitive. For this reason the trapezoid system, though apparently capable of providing the rotations desired, was not investigated in detail.

An interesting alternative for providing rotation about a short radius is to hinge the contact tube itself. By this technique the electrode can be rotated about a relatively short radius while the torch itself does not experience drastic accelerations. A rather crude "first version" of such a device, as pictured in Figure 36, was demonstrated to be effective in welding tests. The electrode could be fed past the hinge in the contact tube with no difficulty. The hinged end of the contact tube was connected by mechanical attachment to the lever shown to the side of the torch. By oscillating the lever at the required frequency and through the required angle, the transverse arc oscillation could be programmed. Oscillations in the ϕ direction do not necessarily have to be over a short radius and can be superimposed over the short radius θ oscillations in a simple manner. This device, or an improvement of it, seems to offer the best possibility for increasing the angle of incidence between arc and sidewall.



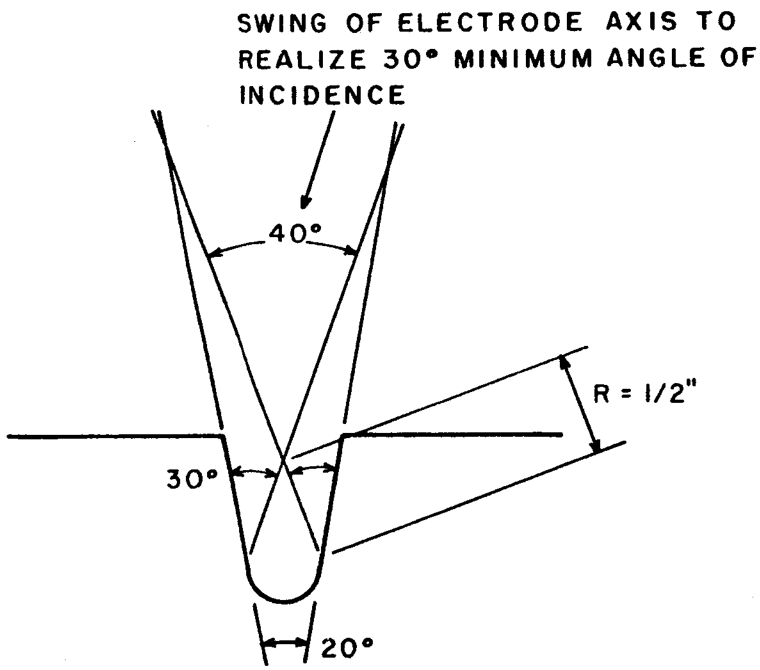


FIG. 35 - CONSTRUCTION OF OSCILLATION GEOMETRY TO OBTAIN 30° ANGLE OF INCIDENCE IN 20° GROOVE.

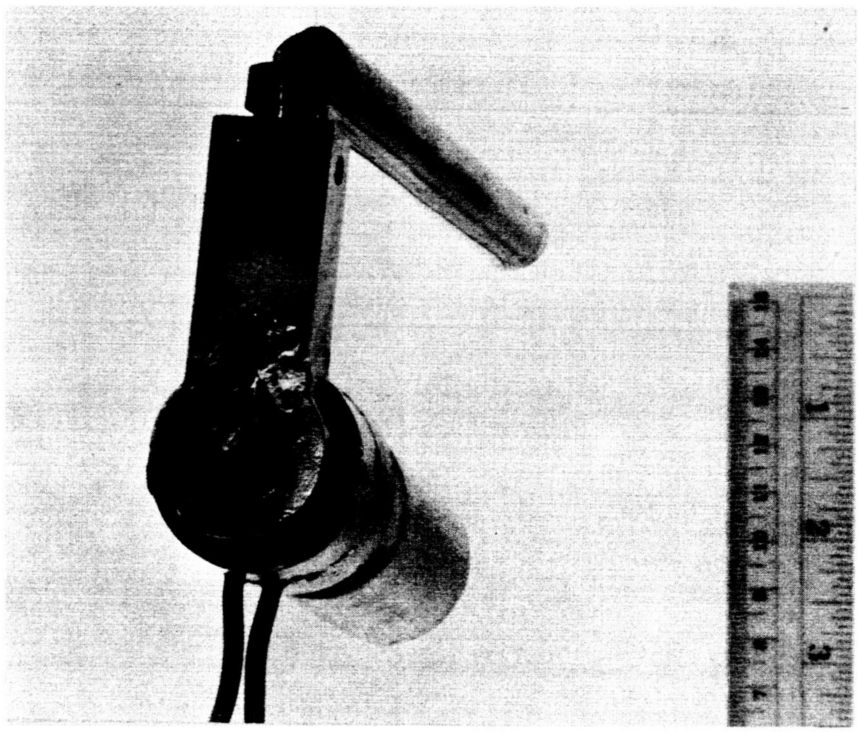


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FIG. 36 - HINGED CONTACT TUBE FOR MECHANIZING OSCILLATIONS ABOUT A SHORT RADIUS.

Oscillations about such a short radius will tend to deposit beads with an over-all concave surface. This surface is not desirable since it is more prone to shrinkage cracking at the bead centerline. Therefore, it is likely that Y direction movements would be required of twice the frequency as the θ oscillations. As the arc swings across the bead, the gun should retract in the Y direction to maintain a flat bead surface.

A third technique that was considered for obtaining a greater angle of incidence is the device pictured in Figure 37, which has a bent contact tube. With the bent tube, transverse (X) motions can be obtained by rotating the torch about its long (Y) axis. An important limitation of this technique is that X and Z movements are no longer independent of each other; the oscillation pattern must take the form of an arc of a circle. By varying the bend angle and the angle of rotation about the Y axis, the radius of this arc can be varied, but this may not be sufficient latitude. However, with short radius arcs this oscillation is not too radical a departure from the chevron pattern found effective by the manual welders, and in any case it is probably a favorable deviation from the linear weave pattern.

C. Automatic Feedback Oscillation Control

Another attractive capability which might be designed into an automatic weave welding machine would be a feedback system of oscillation control. A feedback system requires that some signal be generated which can be used to control the oscillation motion. In reviewing the oscillograph traces of both manual and machine welds of Figures 6 and 21, it can be seen that as the sidewall is approached a rise in current is observed. This current rise is more notable in some cases than in others, but is fairly consistent. A very good example of this relationship is illustrated by the oscillograph trace of a manual weld which is reproduced in Figure 38. It is quite possible that welding parameters can be adjusted to accentuate this characteristic, and thus make it more useful as a signal. For example, its primary cause is a reduction of arc length as the arc falls on the sidewall rather than on the groove root. Two techniques to accentuate this current rise would be (1) the use of an inert shielding gas which has a relatively high voltage drop per unit length of arc plasma; the arc

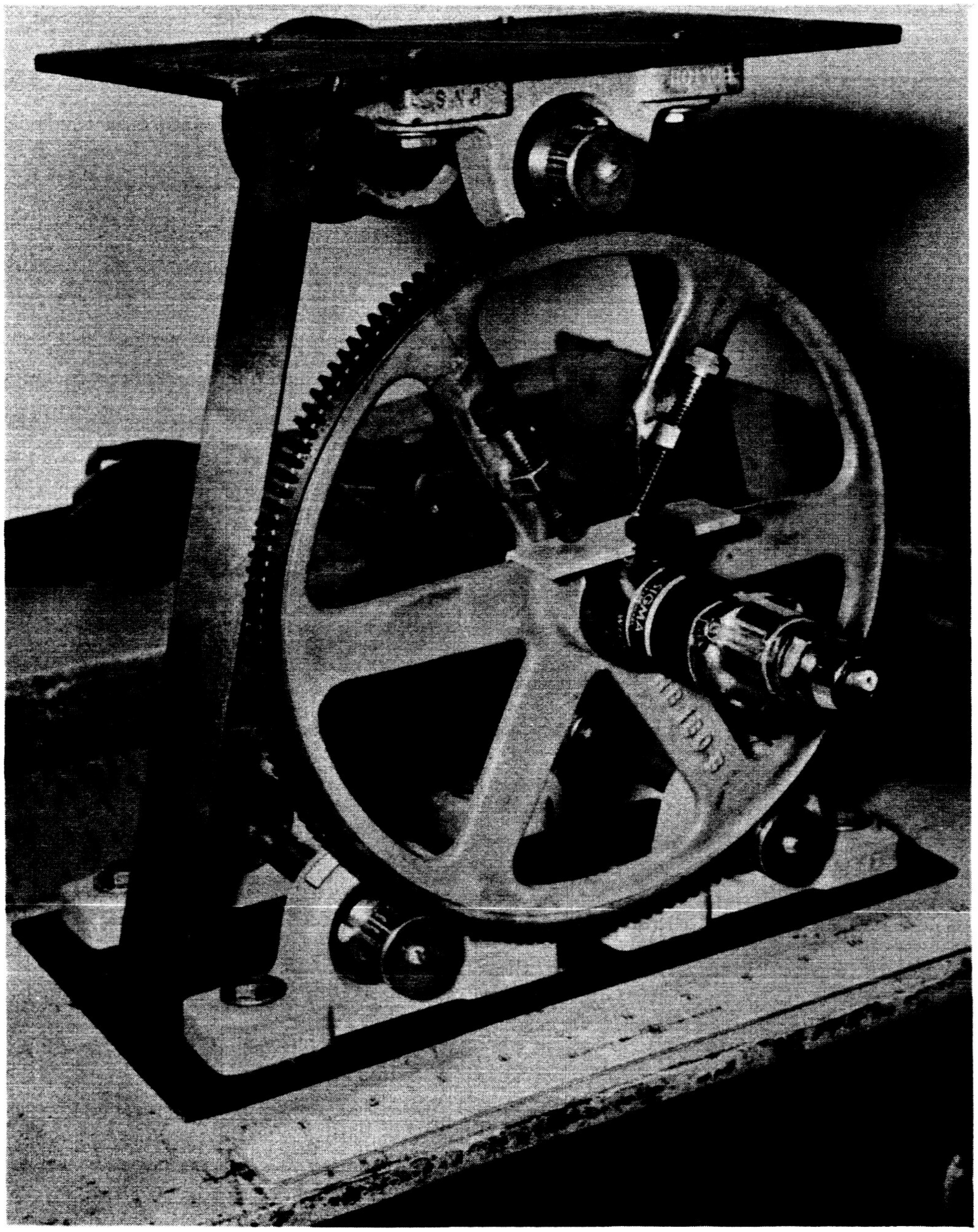

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FIG. 37 - APPARATUS INCORPORATING BENT CONTACT TUBE CONCEPT.

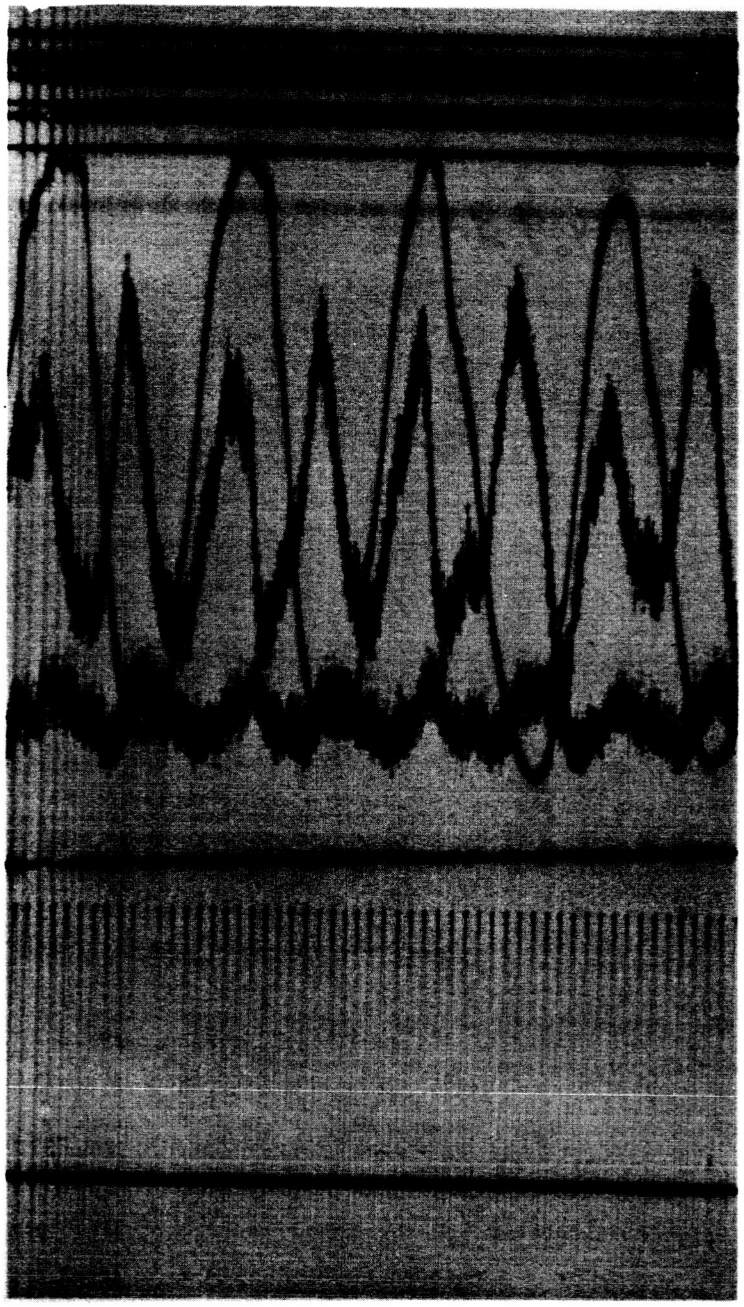

FIG. 38 - OSCILLOGRAPH RECORDING OF AMPERAGE FLUCTUATIONS THAT MAY BE USED FOR CONTROL PURPOSES.

will therefore exhibit a pronounced decrease in resistance as the length decreases, and (2) the use of a power source with a rising characteristic, which will provide a more marked current surge when the resistance of the arc decreases. In any event, the occurrence of surging is fairly reproducible under some conditions and can probably be made more so after experimentation. If the current rise is a dependable signal of the approaching sidewall, it would be a relatively simple matter of circuitry design to use this signal, through a series of relays, to cause a reversal in the transverse arc motion. It is quite possible that an air motor or a pneumatic or hydraulic cyclinder drive would be preferable to electric motors for this device, since reversal currents in electric motors tend to overheat the motor. A system of magnetic clutches may be satisfactory with electric motors. These systems can be made to have short response times and should prove satisfactory.

D. Programmed Arc Power Variation

Variation of arc power parameters (current and voltage) was considered as a means to control the arc force. Experiments with periodically varying arc voltage were successful in that it was shown that power source output voltage variations could be programmed with the frequency required as shown in Figure 39. However, time did not allow any experimentation on the utility of these programmed voltage variations for increasing the latitude of the weave bead welding process. It is interesting to note that arc current also dips when the supply voltage is reduced momentarily. This variation might be utilized according to the following argument. As the sidewall is approached, high heat is required to attain adequate temperature for fusion. However, toward the end of the period of dwell at the sidewall it would be advantageous to reduce the arc force, thus reducing the tendency to blow metal away. Then as the arc just moves away from the sidewall, it would be advantageous to suddenly increase arc force to blow metal back from the receding arc toward the sidewall to provide satisfactory filling and give a desirable wetting angle. This argument is, as mentioned, hypothetical and should be experimentally verified.

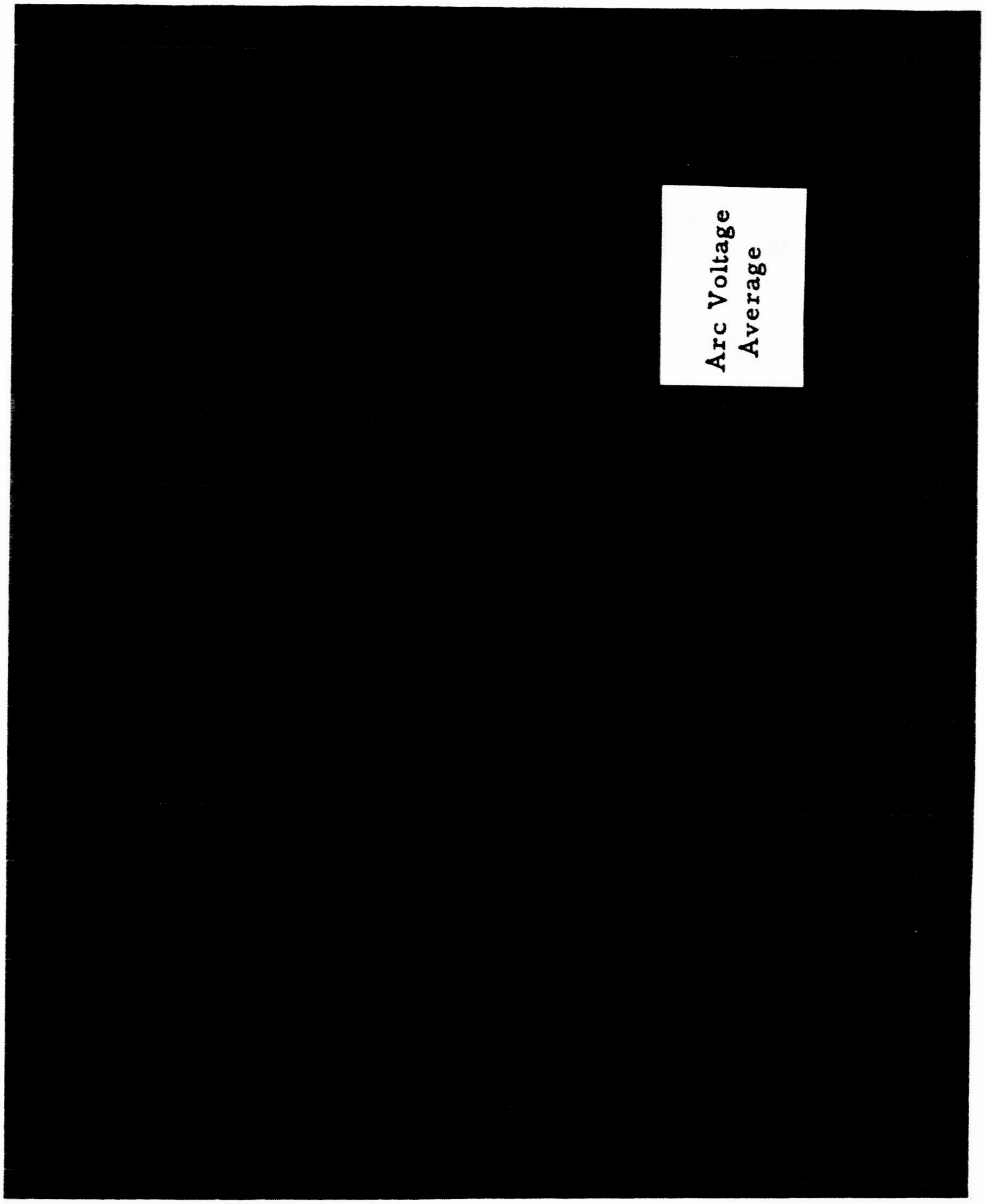

FIG. 39 - PROGRAMMED ARC VOLTAGE.

Voltage control is electronic, actuated by microswitches from the same cam shaft as that which controls mechanical movement, Figure 17 and 18. The microswitch initiates a change in the control circuit, and that change is revoked by a timer.

Similar techniques were used to change current directly by adjusting wire feed, but the results were not promising.

VI. SUMMARY AND CONCLUSIONS

The important conclusion of the program is that a machine was developed which was demonstrated to be capable of performing automatic, vertical-up, MIG welds in aluminum with a programmed weave oscillation. In developing this machine, and in arriving at the machine parameters required to perform satisfactory welds, a great deal was learned about the important characteristics of the weave patterns. This was based on observations of both manual and automatic welding procedures.

Manual welding techniques for performing vertical-up welds in thick aluminum plates with wide weave beads were described. It was observed that a wide variety of oscillation patterns could be made to perform a satisfactory weld by expert manual welders. The choice of pattern was somewhat dependent on groove design and the number of passes allotted to fill the groove. The prevalent patterns were a triangle, a chevron, and a simple lateral weave, all superimposed on a continuous travel motion. The first two patterns were found preferable when filling a relatively narrow groove in a minimum number of passes.

In spite of the wide variety of manual weave patterns which might be selected, the reproducibility of any pattern, once started, was high. The frequency and amplitude of oscillation were remarkably consistent. Because of its simplicity, major study was devoted to the simple weave pattern. The important aspect of performing a successful weld with this, or with the other patterns, seems to be maintaining proper control over heat and filler metal placement. The welder uses the force of the arc to keep the liquid puddle in place. He uses heat input as controlled by welding current and travel speed to limit the size of the puddle to one which can be controlled. He develops a technique which will avoid excessive melting of the sidewall of the groove--which would cause undercut--and also prevents liquid filler metal from coming in contact with solid base metal which is too cold or insufficiently cleansed (oxide barrier not removed) to provide adequate fusion.

The simple transverse weave pattern which the manual welder uses is neither linear or sinusoidal. The transverse motion of the arc in the weld bead takes the form of a slow approach to the sidewall, a dwell near the sidewall, a rather sudden retraction from the sidewall, a rapid deceleration after retraction, and the start of another relatively slow approach to the other sidewall. The usual oscillation frequency is on the order of 8 to 10 cycles per inch of weld, or, considering a normal over-all speed along the seam of 4 to 6 ipm, an oscillation frequency of 1 cycle every 1 to 1.5 seconds. The welding arc was consistently rather short, with current density ajusted to be on the high side of the "drop transfer" range. Either 3/64 in. or 1/16 in. electrode wire can be used.

In making the oscillations the welder establishes a forehand angle of 10 to 20°; the exact angle within this range apparently is not too critical. However, smaller forehand angles or a backhand angle results in undercut. The transverse motion is, for all practical purposes, a translation rather than a rotation. That is, the axis of the electrode and torch remains very nearly parallel to a plane which is normal to the plate and contains the weld seam.

Best results were obtained in performing automatic machine controlled simulations of these techniques when the simpler weave pattern was used as the model. Some experiments were done with complex two-dimensional motions to simulate chevron or triangular patterns, but the advantages which the manual welders could apparently obtain with these patterns were not obtained, within the extent of experimental effort which could be devoted to this phase of study, with automatic simulations. The simple weave pattern parameters were quite similar to those described briefly above for manual welders. The most critical control parameter was the nearness of approach of arc to sidewall. If the proper approach could be established, satisfactory wetting and bead geometry near the wall could be realized. Other parameters were the percent dwell time near the sidewall, the frequency of oscillation, the speed of welding along the seam, and the groove geometry. With narrow-angle grooves (20°) the parameters controlling sidewall geometry became critical. With wider grooves (90°) the sidewall parameters were less critical, but the excessive width of the weld bead, with thicker plates, presented problems during the traverse phase of the oscillation. These problems essentially resulted from very high transverse speeds, approaching velocities of greater than 100 ipm. The latter problem could be avoided by reducing the welding speed.

It is felt that further pursuit of these experiments, with better definition of the causes of the defects and the importance of particular parameters in the oscillation cycle, would be very informative and would advance the art of welding. In addition to those parameters which fall in the category of simulations of manual welding techniques, several other parameters can be considered in an automatic weld which are not available to the manual welder. Brief consideration was given to the use which might be made of these parameters. Some parameters which should be given further consideration as this philosophy of welding is developed include (1) the possibility of controlling the oscillation pattern through a feedback control which senses the approach of sidewall through the influence of this approach on the arc power variable. It was found that welding current exhibited marked variations as a function of approach to the sidewall; (2) the possibility of utilizing a programmed and periodic change in arc voltage as a function of position in the weave pattern; (3) further studies of the improvement in process latitude which might be obtained by incorporating two-dimensional patterns; and (4) further study of the benefits which may be derived by incorporating oscillations about a relatively short radius such that larger angles of incidence can be obtained between electrode and sidewall in narrow grooves.

VII. LOGBOOKS AND CONTRIBUTING PERSONNEL

The experimental data for this program are recorded in IITRI Logbooks No. C12792, C12907, C12915, C12919, C13025, and C13152.

Personnel who contributed to this project include David C. Brown, (formerly with IITRI as Research Engineer), John F. Rudy, Manager, Welding Research; Gene Strojny, Technican; Earl Stridde, Technican; and John E. Anderson, Assistant Experimentalist.

Respectfully submitted,

IIT RESEARCH INSTITUTE

John F. Rudy, Manager
Welding Research

JFR:bj
Tech Rev WR

APPENDIX A

OPERATION OF EXISTING APPARATUS

The control panel for the present wide-weave welding apparatus is shown in Figure 40. The location of this panel, with respect to the mechanical components, was shown in Figure 18 in the body of the report.

The function of the switches and knobs of Figure 40, taken in vertical rows from top left are:

Master AC (top)	Power switch for panel
Arc Length A	Controls arc length (power source voltage) when power source "Remote Arc Length" switch is activated.
Arc Length B	Controls variation in arc length when this parameter is programmed. Both rheostats must be adjusted if either is changed. Arc length is programmed by activating Agastat timer with "AGA Con Vert Travel" switch and throwing "Agastat Con Wire Feed/Arc Volts" switch to right.
Master AC (bottom)	A second power switch.
Programmed Arc Length	Connects Agastat timer relay to "Arc Length B" rheostat.
Wire Feed	Rheostat for controlling wire feed.
Programmed Wire Feed	When off (engaged), wire feed is controlled at Airco wire feed unit; when on (opened), wire is controlled by wire feed rheostat on this panel provided Airco wire feed is set at zero. For programmed wire feed (varying), both wire feed rheostats are used, and the timer circuit activated by switches "AGA Con Vert Travel" (Agastat Controlled Vertical Travel) and "Agastat Con Wire Feed/Arc Volts" to left, alternately shorts the panel rheostat to provide variation in wire drive.

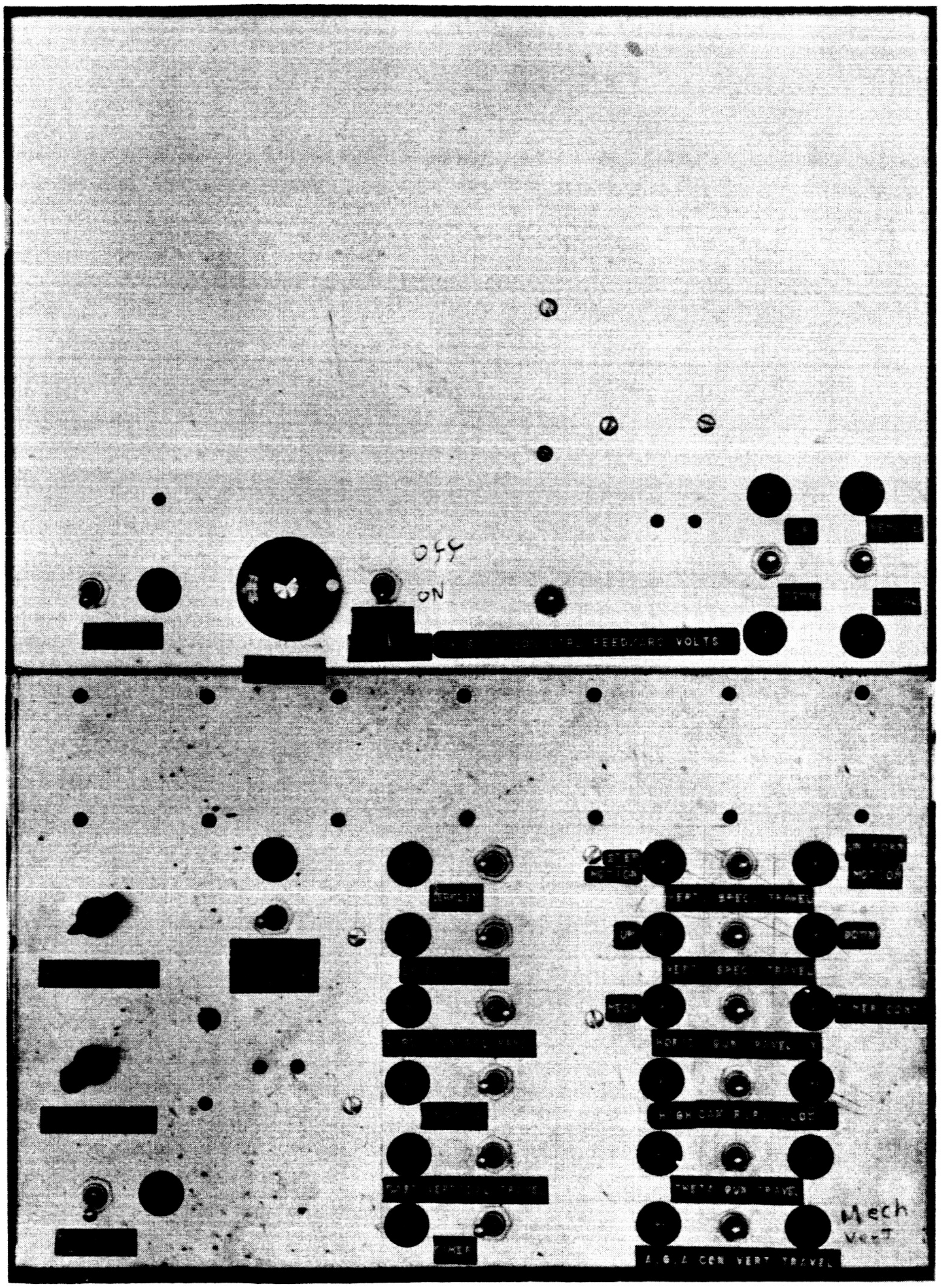

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FIG. 40 - CONTROL PANEL OF WIDE-WEAVE WELDING APPARATUS.

Berkeley	Directs main power to Berkeley specimen travel unit.
Shielding Gas	Activates shielding gas solenoid.
Airco Control Panel	Directs power to Airco control panel.
Contactor	Closes weld current contactor.
Fast Vertical Travel	Directs uninterrupted power to "Slo-Syn" motor which is used to provide step travel motion for specimen.
Timer	Activates "Eagle Timer" which is not used.
Agastat Con Wire Feed/Arc Volts	Places programmed wire feed and arc length circuits in series with Agastat switches or cam-operated microswitches.
Up-Down	Travel direction, with neutral off, when Berkeley motor is driving specimen travel.
Remote-Local	Places Berkeley control either on panel (local) or on Berkeley control box.
Vert Spec Travel, Step Motion	Engages "Slo-Syn" Specimen Travel Motor to intermittent output of Eagle timer.
Vert Spec Travel, Uniform Motion	Bypasses Eagle timer for continuous travel via Slo-Syn motor.
Vert Spec Travel, Up and Down	Controls direction of travel by Slo-Syn motor.
Horiz Gun Travel X, Mech	Activates Zero-Max horizontal torch drive motor (Figure 18).
Horiz Gun Travel X, Timer Cont	Disconnected, intended for another horizontal torch drive mechanism which was not installed.
Cam RPM, High-Low	General purpose servo motor used to increase or decrease output rpm to Zero-Max unit, hence that of the cam, and therefore of weave frequency.

Theta Gun Travel	Not connected.
AGA Con Vert Travel	Activates Agastat timer through cam-actuated microswitches.

The above circuits are somewhat redundant. There are two separate motors to provide vertical travel of the specimen (Slo-Syn and Berkeley), and there are two timing circuits (microswitch-actuated Agastat and Eagle).

The two specimen drive units had different attributes, which were complementary. The Berkeley provided a stepless variable speed, uniform travel motion; this unit could not be operated intermittently due to the risk of overheating by high starting currents. The Slo-Syn motor was designed for intermittent operation, but only at a given rpm, adjustable in steps by changing gear ratios. One of the two drive systems must be mechanically disconnected at all times to prevent binding.

The two timing systems also had complementary attributes. The Eagle timer had more switching circuits and could control more parameters. However, microswitches operated by the primary cam shaft, in conjunction with Agastat time delays, were easier to synchronize with the weave oscillation pattern.

The above panel provides control over frequency of weave pattern, and the welding power parameters. Travel speed is controlled by the Berkeley drive. The main switch for welding is in the pistol grip (Figure 18), and the amplitude of weave oscillation is controlled by the mechanical placement of the fulcrum with the crank shown in Figure 18.

Typical operation sequences are described in the following paragraphs.

Vertical movement of specimen carriage can be accomplished in two ways. Continuous motion works through a modified Berkeley sidebeam carriage mounted in the vertical position. To operate carriage with the Berkeley, first engage the pinion gear in the rack, turn on the two switches marked "Master AC" and the switch marked "Berkeley." Wait approximately 45 seconds until time delay relay in the Berkeley electronic control unit clicks, then select the speed range and the desired speed by flipping the range switch to either "high" or "low" and adjusting the speed rheostat.

(These controls are located on the front of the Berkeley control.) Next, the switch marked "Remote" and "Local" is turned to "Local"; the carriage will move up or down according to switch marked "Up" and "Down." Once this procedure has been followed, the carriage movement can be controlled with the "Up" and "Down" switch which also has a center-off position.

The "stepping" drive system utilizes the same carriage and beam but with the pinion gear disengaged from the rack. (When this system is used, the Berkeley motor and gear train are not engaged.) A Slo-Syn 72 rpm motor geared down to 10 rpm drives a sprocket and chain assembly. The chain is fastened to the specimen carriage. Stepping motion can now be obtained in either of two ways: through the use of the Eagle timer or through the cam-actuated control system. The latter system is preferred because the stepping motion is synchronized with the weaving motion of the gun, which is driven with the same cam system. To use the cam-actuated stepping motion system, turn on the lower "Master AC" switch on the control board, and turn the switch marked "Horiz. Gun Travel" to the left (this starts the drive motor which turns the cam). Turn the switch marked "AGA Con Vert Travel" to the right; the carriage will now move up or down according to the switch marked "Vert. Spec. Travel" each time the cam engages a microswitch. This motion continues until the Agastat delay opens the motor circuit.

The horizontal travel of the gun is controlled by the switch marked "Horiz. Gun Travel." When the switch is flipped to the left, it activates a Zero-Max variable-speed motor. This, through a system of cams and arms, gives the gun horizontal motion. The switch marked "High-Cam RPM-Low" activates a Slo-Syn 72 rpm motor which is connected by sprocket and chain to the speed control on the Zero-Max drive motor. By flipping the switch to high or low, the oscillation frequency of the horizontal motion can be increased or decreased. The wire feed speed (welding current) control is located on the lower left corner of the upper control panel.

The actual procedure of making a weld consists of the following steps:

1. The specimen is placed on the carriage
2. Turn on both "Master AC" switches
3. Turn on "Berkeley" control switch
4. Turn on Airco control panel
5. Turn on Vert. Spec. Travel to uniform motion
6. Set wire feed speed
7. Turn to "Local" switch
8. Turn on Contactor
9. Turn on Shielding Gas (and allow to flow for about one minute)
10. Turn on Airco Power Supply
11. Turn on Horiz. Gun Travel*
12. Turn to Down
13. Press button control gun handle, and start welding.

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* When welding in the 20° groove, this switch is not turned on until the arc is established.

APPENDIX B

LAYOUT DRAWING OF WIDE-WEAVE APPARATUS

MODEL B

Enclosed with this report is a layout drawing of an apparatus which is similar to the apparatus used for experimentation on this program--Improved Model B Wide-Weave Welding Apparatus. The operation is as follows: Variable-speed drive rotation is applied to shaft (Plan View and View A-A). This rotates all cams and thus determines frequency of weave pattern. Power is transmitted through gears to left-hand X, θ cam shaft, and through 3 chain drives to right-hand X, θ cam shaft. These cams alternately push cam follower back and forth in the X direction (horizontal) (Plan View). Dwell time at each movement extreme is varied by changing the spacing between the LH and RH X, θ cams; wider spacing introduces mechanical play and increased dwell time. This is achieved, during welding operation with the indicated dwell time adjustment crank (Plan View and View A-A).

The amplitude of horizontal weave motion is continuously variable--during welding operation, if desirable--by adjusting the lever fulcrum with the indicated hand crank (Plan View and View D-D). This horizontal motion is transmitted to the welding gun through the tie rod connection system (Plan View and Gun Mount Assembly). A bias on this movement provides fine-groove following adjustment during welding (Gun Mount Assembly).

Rotation about the ϕ axis, to provide a vertical component to the weave pattern, is obtained through the right angle gear to the ϕ cam shaft and cams (Plan View and View C-C), through the cam follower to the ϕ rotation shaft (Gun Support). The amplitude and pattern of this movement is a function of the ϕ cam; only the frequency can be conveniently changed during operation.

The mechanical support for the gun allows freedom of X translation and θ and ϕ rotation. Either X or θ movement must be prevented (by tightening appropriate set screws) to obtain a controlled horizontal weave oscillation (Gun Support). Gun support and tie rod assemblies should be short and rigid to prevent unwanted mechanical play.

Microswitches for auxiliary functions such as voltage, current, or travel speed variation are mounted adjacent to the microswitched cam shaft and cams (Plan View), which are driven by a chain from the right-hand X, θ cam shaft.

APPENDIX C

LAYOUT DRAWING OF MODIFIED WEAVE CONCEPT

MODEL C

The drawing of Model C illustrates a unit which imparts a variable-amplitude axial rotation and a variable-amplitude swing to a gun mount shaft. These motions are the θ and ϕ rotations, respectively (Detail G). The drive shaft rotates ϕ cam shaft through right angle gears, which rotates the θ cam shaft by a chain drive (View F-F). The θ cam imparts the axial rotation through the cam-slide components of Section D-D and Section H-H. The axially rotating gun mount shaft extends up through this stage to the top stage (Section A-A and Section J-J) where the ϕ cam imparts a swinging motion through the slide components. The pivot point for this ϕ swing is the universal joint contained between decks of D-D and A-A.

The advantage of this unit over Model B is the capability for continuous adjustment of amplitude of ϕ. However, a marked disadvantage is the inability to adjust dwell time. New cams would be required for each dwell setting.